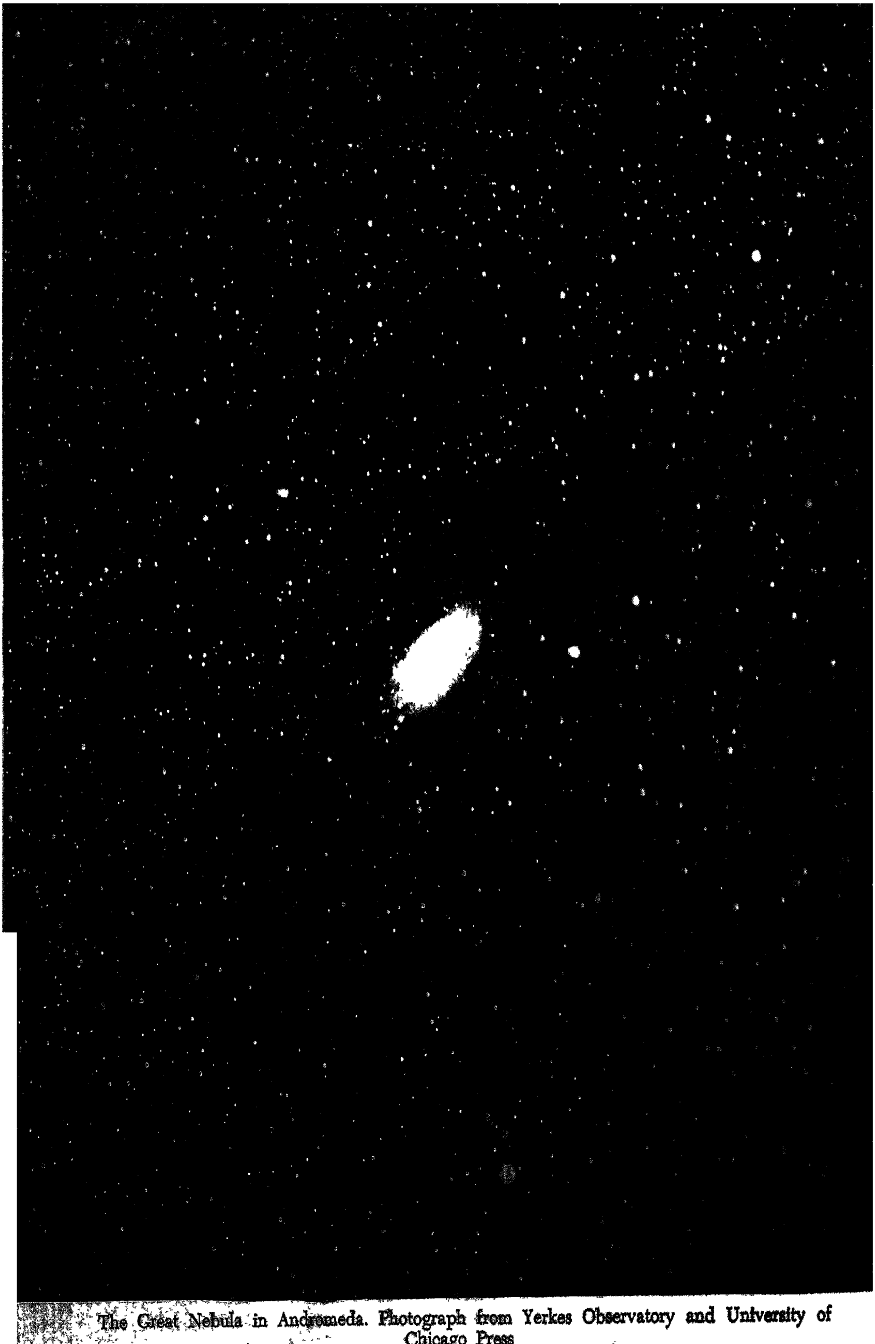
Astronomy, Maps, and Weather



The Great Nebula in Andromeda. Photograph from Yerkes Observatory and University of Chicago Press

Astronomy, Maps, and Weather

By C. C. WYLIE
PROFESSOR OF ASTRONOMY
STATE UNIVERSITY OF IOWA

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ASTRONOMY, MAPS, AND WEATHER

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Preface

With the entry of the United States into the war on December 8, 1941, the Army Air Corps inaugurated a great plan to train hundreds of thousands of young men for future service as pilots, navigators, and bombardiers for our fighting aircraft. These young men, being educated for peacetime lives, are in general not prepared for the exacting demands of technical warfare. A great emergency training program is necessary to get them ready for the day they enter flight training.

On the recommendation of a committee nominated by Dr. F. R. Moulton, Permanent Secretary of the American Association for the Advancement of Science, and consisting of Professor W. H. Hart of the University of Minnesota, Professor W. M. Whyburn of the University of California at Los Angeles, and the author, the Army Air Corps has announced a plan for training in mathematics and the physical sciences that extends from high school through college. This program is to be an integral part of the Army Air Corps Reserve, in which young men can enlist while continuing their college studies. In their own colleges they will follow a normal curriculum with the addition of certain specified courses. Among these courses is one in astronomy, maps, and weather.

At the request of the Army Air Corps Flying Training Command, this book has been prepared to meet the needs of this course. It stresses familiarity with the constellations and brighter stars; a conception of the Earth in space; the motions of the Earth; the fundamentals of time, with practice in the use of navigational timepieces; the determination of longitude, latitude, and Sumner lines; map construction and map reading; and the principles of meteorology, particularly weather forecasting from immediate observational data.

The preparation of a new and fundamentally different text within a few months has been possible only with great cooperation.

Acknowledgment must be made to the office of the Chief of the Air Corps and to the officers of the Army Air Corps Flying Training Command for their assistance in outlining the course. Thanks are also due Mr. C. B. Watts, Dr. L. R. Wylie, and Mr. F. P. Scott, all of the U. S. Naval Observatory, for checking the manuscript. The list of pronunciations of the names of stars and constellations was supplied by the Rev. D. J. McHugh, of De Paul University, to whom I am very grateful. And finally, special thanks must be given to Miss Goldie Sexton and Miss Helena Briggs for their continual assistance since the project was first undertaken.

August 1, 1942

C. C. WYLIE
University of Iowa

Introduction

This book has a novel title and treats an unprecedented combination of subjects. It points out new relations between scientific theories and urgent practical problems of the day. Its science is illuminated by the applications; its applications rest on fundamental scientific theories. Both the pure science and the applications are enriched by their combination in one volume.

It will be inferred, correctly, that this book has a dual purpose—to expound the essentials of certain fields of science and to provide basic information for specific applications. The problem of writing a dual-purpose book—of killing two birds with one stone—is a difficult one to solve. If an author mixes the two purposes throughout his book, he is likely to lack clarity and to fail to achieve either purpose. If he follows one purpose to the end before considering the second, he is doing little more than writing two books.

This volume consists essentially, though not formally, of four rather distinct parts. The six chapters of the first part are devoted to such subjects as the celestial sphere, the constellations (with 14 maps), telescopes and the earth—subjects that are basic for both astronomy and navigation. The second group consists of three chapters, on weather, clouds and weather forecasting, respectively. At this point in the book it would be possible to go on with astronomy or to take up navigation. The author adopts the latter plan.

The group devoted to the general subject of navigation consists of three chapters on maps, time, and celestial navigation, respectively. In these chapters, as well as in the preceding three, the prospective airplane pilot or navigator finds information of the highest importance. If he reads the book attentively he will find that the earlier material has laid solid foundations for forecasting weather and navigating a plane by celestial means.

The final eight chapters consist of discussions of celestial bodies

ranging from the moon to exterior galaxies of stars. They give a good general idea of the universe of the astronomer and lead an inquisitive mind along from one wonder to another. The author has not only achieved a large degree of unity in his treatment of many subjects but he has arranged the material so that that which is least important for navigation may be conveniently omitted until conditions are more favorable for reading and enjoying it.

F. R. Moulton
Permanent Secretary
American Association for the
Advancement of Science

Astronomy, Maps, and Weather

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The Celestial Sphere

The blue vault of the sky, as it appears to be spread above us, is termed the celestial sphere. This imaginary vault, against which the heavenly bodies are seen, is so far distant from us that, if any two parallel lines from different parts of the Earth are drawn to this sphere, they will appear to come together. Of course this cannot be a fact, but the distance of the stars is so immense, that we are unable to distinguish the little difference of four, or even eight, thousand miles, and the two lines will seem to unite, even with the most powerful telescope. We consider this great Earth as a mere speck or point at the center of the celestial sphere.

The Celestial Sphere Is at an Infinite Distance. At the distance of the stars we can neglect even the diameter of the Earth's orbit, since if we should draw two parallel lines, one from each end of the Earth's orbit, to the sphere, although these lines would be 186,000,000 miles apart, yet they would be extended so far that we could not separate them with the ordinary telescope, and they would appear to pierce the sphere at the same point. Consequently, in all parts of the Earth, and in every part of the Earth's orbit, we see the fixed stars in the same place. The stars are so far away that, for practical purposes, they can be considered as being at an infinite distance. It is convenient, therefore, to consider the celestial sphere, against which they are seen, as at a mathematically infinite distance.

This sphere of stars surrounds the Earth on every side. In the daytime we cannot see the stars because of the superior light of the Sun, but with a telescope the brighter stars can be observed. On clear days an astronomer can find the brighter stars just as readily at noon as at midnight. One half of the sphere is constantly

visible to us, and so far distant are the stars, that we see just as much of the sphere as we would if the upper part of the Earth were removed, and we were to stand four thousand miles farther away, or at the very center of the Earth, where our view would be bounded by the lower half of the Earth.

Apparent Angles. When we look at a distant object, it is difficult to estimate its real diameter, but its apparent diameter can be estimated readily. For example, when we look at the Moon, its real diameter must remain quite unknown until the distance is measured. The apparent diameter can be measured roughly, however, by tying two strings across the end of a cardboard tube and adjusting the strings so that the space between them marks the diameter of the Moon when the other end of the tube is held to the eye. If this is done, and then lines are drawn at the angle which the two strings make with the eye, it is found that the apparent diameter of the Moon measures just about half a degree. No appreciable difference will be found when the Moon is near the horizon and when high in the sky.

The apparent diameter of the Sun can be measured in the same way, but heavily fogged film should be used to protect the eye when looking at the Sun. The angle representing the apparent diameter of the Sun will be found to be just about half a degree. In other words, the apparent diameter of the Sun is practically the same as the apparent diameter of the Moon. It is interesting to note that if the Moon appeared much smaller or much larger than the Sun, we would not have the splendid views of eclipses which astronomers now travel thousands of miles to see.

Apparent distances in the sky should be expressed in angular units, usually degrees, for there is no meaning in the statement that an object appears "10 feet" above a certain star. The real distance of two stars may be millions of millions of miles, but if a person mentally places the sky at a distance of only 100 feet they may appear only 10 feet apart. If another person mentally places the sky at 200 feet, the same stars would appear 20 feet apart. Neither man would realize that he is placing the sky so close.

Measuring Sticks in the Sky. Often persons with no astronomical training observe meteors, and occasionally they observe comets, not seen by professional astronomers. To change the recollections of such persons from "feet" into angular measure, it is necessary

to have some "yardsticks" in the sky. For small angles, the apparent diameter of the Moon, almost exactly half a degree, is convenient. For example, when a man sees a large meteor which appeared "six inches" across, he is asked to compare the apparent size of the meteor with the apparent size of the Moon.

For somewhat larger angles, the pointer stars of the Big Dipper form a convenient "measuring stick." They are just about five degrees apart. For still larger angles, hold the hand at arm's length with the fingers and thumb extended. The distance from the end of the thumb to the end of the little finger is just about 20 degrees.

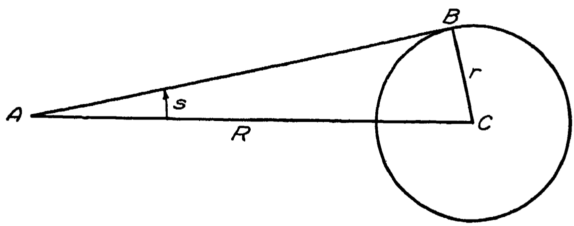


FIG. 1. The Apparent Semidiameter of a Celestial Body

Another measure useful in the United States and Europe is the altitude of the North Star, which is approximately equal to the observer's latitude. An average good visible horizon on land is two or three degrees above the true horizon, so that the apparent distance from the North Star to the visible horizon will be a little less than the latitude. Finally, the distance from the visible horizon to the zenith will be just a little under 90 degrees, on land.

Distance and Apparent Size. Most of the heavenly bodies are spherical, or nearly so. Suppose (see Fig. 1) the radius BC is equal to r, and that the object is seen from the point A, whose distance is AC, or R. Then the apparent, or angular, semidiameter is BAC, or s.

The angle ABC is a right angle, and

$$\text{Sin } s = r/R.$$

The diameters of the heavenly bodies are very small compared with their distances; so that for most work the sine can be assumed equal to the arc. This gives, in radians,

$$s = r/R.$$

Reducing to ordinary angular units

$$s^\circ = 57.3\ r/R \qquad\qquad s'' = 206265\ r/R$$

For the Moon, the closest of the heavenly bodies excepting meteors, $R = 239{,}000$ miles, and $r = 1080$ miles, whence $s^\circ = 0.^\circ 259$, or a little over a fourth of a degree. Expressed in radians, $s = 1/221$, or it is equivalent to one foot seen from a distance of 221 feet. The angular diameter, which is twice the radius, is equivalent to two feet seen from a distance of 221 feet, or one foot seen from a distance of 110 feet. Of course, any other unit could be used instead of feet. For example, the angular diameter of the Moon is equivalent to one centimeter seen from a distance of 110 centimeters.

Locating Points on the Celestial Sphere. Every one is familiar with the method of locating one's home as being in a certain city, or, more approximately, as being in a certain state. This method is also used for objects in the sky. A star may be located as being in a certain constellation, as for example, in Orion. We can, however, place our house more accurately as being in a certain block on a certain street, and likewise, we have more specific locations for the stars on the celestial sphere.

To locate a point on a sphere more accurately, one uses coordinates based on a fundamental circle, and a point on that fundamental circle, called the origin. On the Earth the equator is adopted as the fundamental circle and the intersection of the meridian of Greenwich with the equator is taken as origin. Latitudes are measured north and south of the equator, and longitudes are measured east and west of the meridian of Greenwich. Latitude and longitude will be discussed more fully later.

On the concave surface of the celestial sphere three primary circles are imagined drawn for the more common problems of astronomy. These are the celestial horizon, the celestial equator (or equinoctial), and the ecliptic.

The Horizon System. The *celestial horizon* is a great circle defined by the intersection of a plane perpendicular to the plumb line and the celestial sphere. This plane may be thought of as passing through the observer, or through the center of the Earth, whichever is more convenient. As explained previously, the differ-

ence of less than 4000 miles is negligible at the distance of the celestial sphere.

The *visible horizon* is the line where the Earth and sky seem to meet. On land, it is irregular, but at sea it is a circle, though not a great circle. The surface of the ocean must be level, but if the observer is several feet above the water level, he will be able to see below the true horizon. The correction for this, known as dip of the horizon, is quite simple for the navigator of a ship. The correction is much larger for the pilot of an airplane since he may be thousands of feet above the level of the visible horizon.

In reasonably open and level country the visible horizon is usually two or three degrees above the true one. This can be determined easily by timing the rising and setting of heavenly bodies, as for example, the setting of the Sun. In ordinary level but rolling country one must be on the top of a hill to see the Sun set as late as the calculated time of true sunset. The astronomer usually defines the plane of the horizon with a surface of mercury, which by physical laws must be a level surface. Explorers and other persons using a sextant on land also use an "artificial horizon" of mercury. Engineer's transits have spirit levels. Aviators generally use a bubble built into a sextant, or octant, to determine the plane of the celestial horizon.

The *zenith* is the point directly overhead, where the plumb line extended would intersect the celestial sphere, and the *nadir* is the point directly beneath.

The *celestial poles* are the points where the Earth's axis extended would cut the celestial sphere. The north celestial pole is near the star Polaris, at present.

The *meridian* is a great circle passing through the celestial pole and the zenith; the two intersections of this circle with the horizon are the north and south points. The Sun is on the meridian at true noon.

Altitude is the angular distance in degrees measured from the horizon upward, along a great circle passing through the zenith and perpendicular to the horizon. Such circles are called vertical circles. (See Fig. 2, page 7.)

Azimuth is the horizontal projection of the direction of an object. Navigators usually measure azimuth from the north point around

through either the east or the west to 180 degrees. Azimuth is measured in degrees. (See Fig. 2.)

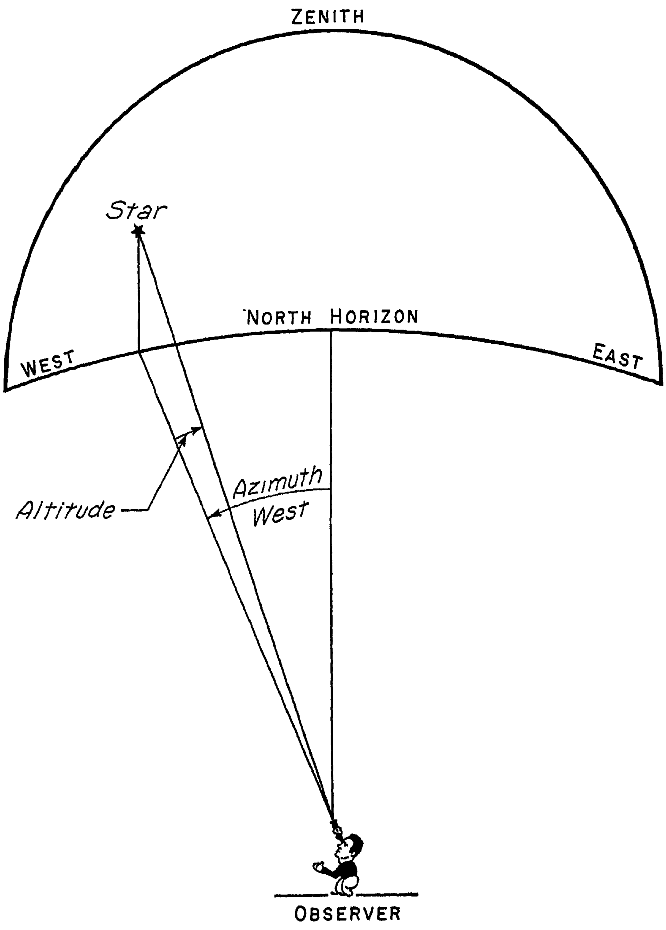


FIG. 2. The Concepts of Azimuth and Altitude

Altitude and azimuth, coordinates based on the plane of the horizon as fundamental, fix an object with respect to terrestrial

landmarks. The engineer measures altitude and azimuth with his transit. The navigator measures altitude with his sextant, and reads azimuth from his compass.

If, however, one sets an engineer's transit on some heavenly body in the eastern sky, and records the altitude and azimuth, he will see that five minutes later the instrument is no longer pointing at that heavenly body. Evidently the altitude and azimuth are no longer what was recorded. The rotation of the Earth on its axis carries the horizon through a revolution in twenty-four hours. Also, any movement of the observer to a different locality gives him a different horizon. It is evident that a different fundamental plane must be chosen for a permanent catalogue of the positions of the heavenly bodies.

The ancient astronomers used as the fundamental plane that of the orbit of the Earth. This is the *ecliptic*, the great circle where

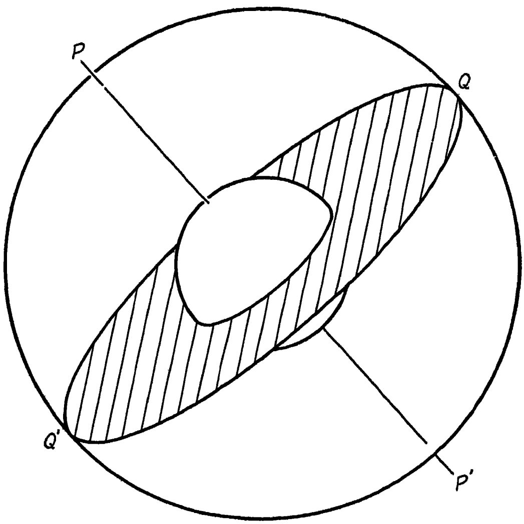


FIG. 3. The Celestial Equator, *QQ'*

the plane of the Earth's orbit cuts the celestial sphere. As the Earth moves in its orbit, the Sun seems to move along the ecliptic. For certain investigations astronomers still use the ecliptic, and for certain other investigations the plane of the galaxy, or Milky Way,

is used as fundamental, but for most work in astronomy the plane of the Earth's equator is more convenient. The following are the definitions in this system.

The Equator System. The *celestial equator* (or *equinoctial*) is the great circle in which the plane of the Earth's equator cuts the celestial sphere as shown in Fig. 3. It passes through the east and

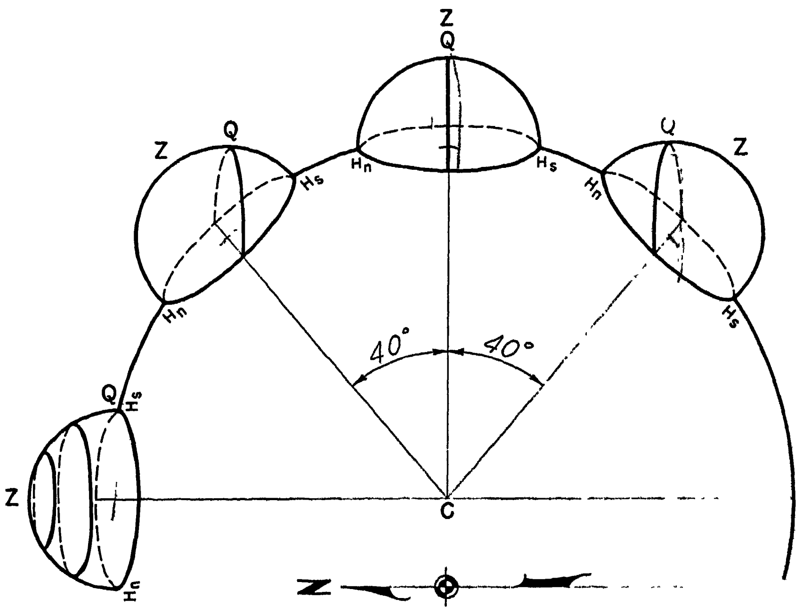


FIG. 4. The Celestial Equator *Q*, and the Zenith *Z*, in Various Latitudes

west points of the horizon. The position of the celestial equator in the sky for various latitudes is illustrated in Fig. 4.

The *vernal equinox* is the point where the Sun, in its apparent annual motion, crosses the celestial equator passing from south to north. This occurs about March 21. The vernal equinox is at one intersection of the ecliptic with the equinoctial. The autumnal equinox is at the other. (See Fig. 5.)

Declination is the angular distance north or south of the celestial equator, counted plus when north, minus when south, and measured in degrees along a great circle which passes through the celestial pole and is perpendicular to the equator.

Right ascension is the angular distance measured eastward from the vernal equinox along the celestial equator. It is measured usually in units of time of hours, minutes, and seconds.

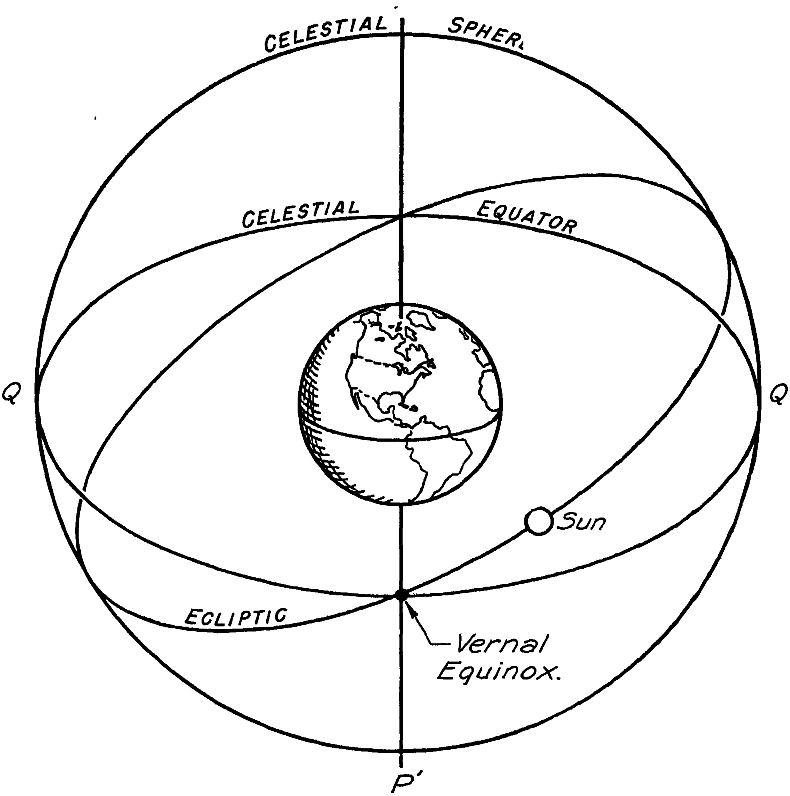


FIG. 5. The Vernal Equinox Is Marked by the Intersection of the Ecliptic and the Celestial Equator

Right ascension and declination, then, fix the location of points on the celestial sphere with respect to the stars, so star charts are drawn on those coordinates, just as maps of the World are drawn in longitude and latitude. The chart in the back of the *American Air Almanac*, or the *American Nautical Almanac*, is plotted in right ascension and declination; and for the fifty-five navigational stars

listed on the inside of the back fly leaf, the right ascension and declination are given.

Relation between Degrees and Hours. The Earth rotates on its axis once in twenty-four hours, so the heavenly bodies are turned at the rate of $360°/24^h$, or 15° per hour. Because of this motion, it is convenient to measure right ascension in units of time, rather than in units of arc. When reducing from time to arc, and vice versa, the following relations save unnecessary labor.

$$\begin{aligned} 1^h &= 15° \\ 4^m &= 1° \\ 1^m &= 15' \\ 4^s &= 1' \\ 1^s &= 15'' \end{aligned}$$

Do not use the symbols for arc when working with time. The writing of 15′, when 15^m is meant, leads to error.

Exercises

1. What are several measures in the sky which help fix apparent distances in degrees?
2. What is a radian?
   a. Change 90°, 23°, 220°, 360° and 145° to radians.
   b. Change 2, 2π, 0.3, and 1.7 radians to degrees.
3. A boy whose arm is 30 inches long cuts off 20° in the sky between his thumb and little finger when his arm is outstretched. What is his span in inches?
4. How far away must you place a yardstick to have its apparent length equal 5°?
5. For what work is the horizon system of coordinates commonly used, and for what is the equator system used?
6. How does a person's visible horizon differ when he is on a flat plain, in an airplane at several thousand feet altitude, on a ship at sea, and in a large city?
7. Be able to point out in the sky the following: zenith, nadir, celestial poles, altitude, meridian, azimuth, declination, right ascension, vernal equinox, and the ecliptic.
8. What is the declination of an object which rises due east?

9. What is the azimuth of due west, south east, and north west?
10. Where do the celestial equator and the ecliptic intersect?
11. What are the right ascension and declination of the sun when it is at the vernal equinox?
12. Show the relationship between hours and degrees.
13. Change 90°, 180°, 225°, and 285° to hours.
14. Change to degrees, minutes, and seconds (° ′ ″):

13^h	51^m	15^s
06	24	39
21	09	41

15. Change to hours, minutes, and seconds (^{h} ^{m} ^{s}):

165°	32′	21″
273	44	55
17	03	45

☆ II ☆

The Constellations

In the daytime sky one usually sees only the Sun and Moon. In the night sky one sees the Moon, stars, occasionally meteors, and less frequently, comets. Early people separated the stars into groups, known as constellations. Every one who studies astronomy at all should learn to recognize the constellations and the bright stars, and this is particularly important for those who may go into navigation or exploration.

The Number of Stars. From a casual inspection of the stars on a clear night one might think that the number of stars visible is countless. A Hebrew prophet wrote "Look now toward heaven and tell the stars, if thou be able to number them." Closer inspection, however, shows that the number visible to the eye is far from countless.

The number of stars the average person can see on an ordinary *moonlight* night is shown by the number plotted on star charts, on which only the stars visible on a clear moonlight night are plotted. On one such series of charts, the number varies from 224 to 277. The average person will see less than *300 stars* at one time in the whole sky on an average moonlight night.

The number of stars students with good eyesight could see in the whole celestial sphere on an average clear *moonless* night, has been found from numerous counts in sample regions of the sky. Students with the best eyesight could see about 2500 stars if the entire celestial sphere were visible.

The number of stars that astronomers can see under the best conditions has been found by pointing telescopes with the naked eye. If an astronomer can point repeatedly at a star, so that another person looking through the telescope sees it, it is assumed that the astronomer is seeing it with the naked eye. Some astronomers

can "see" in this way stars fainter than the sixth magnitude (magnitude is defined later), and there are more than 6000 such stars. That is, there are more than 6000 stars bright enough to be seen by a keen eye.

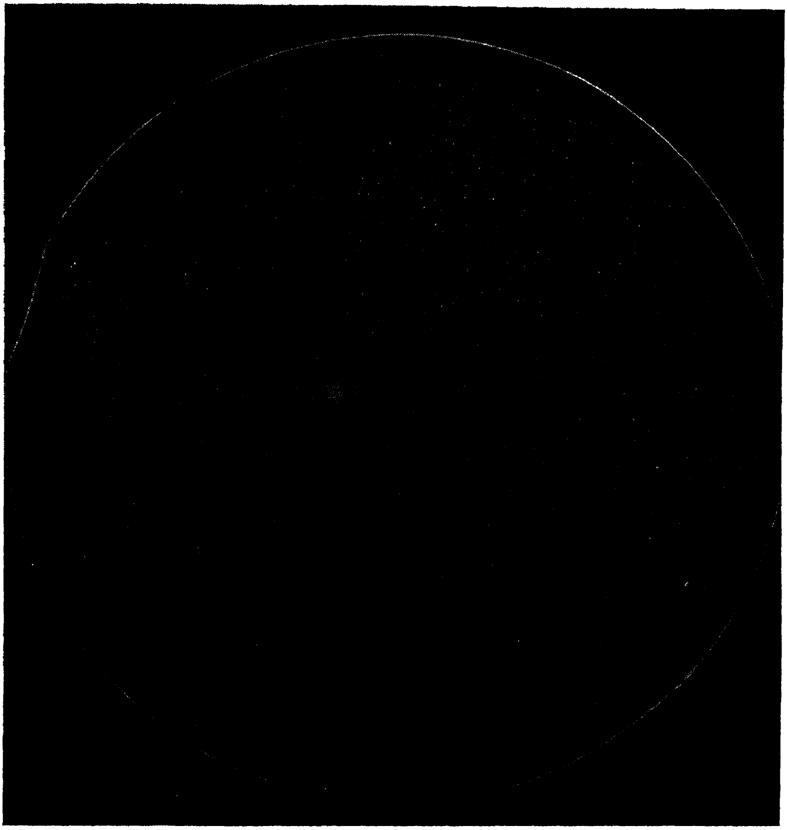


FIG. 6. The Region of Deneb, Photographed with a Schmidt Telescope by Harold Lower

The number which can be seen with the naked eye, well enough to chart the position with some accuracy, is indicated by the fact that catalogues made before the days of the telescope included just over 1000 stars. This number held from classical times until the invention of the telescope.

The telescope increased enormously the number which could be

observed. With a 2 3/4-inch telescope a German astronomer charted more than 300,000 stars north of the celestial equator, or in half of the celestial sphere. From counts of stars on photographs of sample regions of the sky, it is estimated that about one billion stars could be photographed in the entire celestial sphere, with the Mount Wilson 100-inch telescope. Since that telescope reaches the 21st magnitude, there are about one billion stars including that magnitude.

To understand better what is meant by seeing "sixth magnitude stars," look carefully at Alcor, the faint companion of Mizar, in the Big Dipper, on some clear night and compare it with Polaris, the North Star. To see 6000 stars in the whole celestial sphere, one must be able to see stars as much fainter than Alcor as Polaris is brighter. Compare the two stars and see what this means. To understand what is meant by photographing "magnitude 21," try to think of stars as much fainter than Alcor as the full Moon is brighter. The Mount Wilson 100-inch telescope can photograph such stars.

Naming the Stars. The use of proper names is the first, and best known, way of naming the stars. Proper names are used by some for nearly all of the fifty-five navigation stars listed in the *American Air Almanac* and for others. Among well-known proper names are Dubhe and Merak, the "pointer stars," in the Big Dipper; Vega, the bright star in Lyra, the Harp; Betelgeuse and Rigel in Orion; Sirius, in Canis Major, the Great Dog.

A second way of naming the stars is by the letters of the Greek alphabet, followed by the genitive (possessive) of the Latin constellation names. The lower case, or small, Greek letters are the ones used for star names. They are given in order in Table I.

The order in which the Greek letters are assigned is usually the order of brightness, but there are many exceptions. Vega is Alpha Lyrae, and Sirius is Alpha Canis Majoris, in agreement with the general usage. In Orion, however, Betelgeuse is Alpha Orionis and Rigel is Beta Orionis, although Rigel is brighter than Betelgeuse. In the Big Dipper, the Greek letters are assigned in order of position rather than order of brightness, as in that configuration, position is easier to remember than brightness.

A third way of naming the stars is used in the catalogues. A star is referred to by the catalogue, and the number in that cata-

logue. For example, Boss 1646 refers to the star numbered 1646 in the *Preliminary General Catalogue* of Lewis Boss.

TABLE I. THE GREEK LETTERS

α Alpha	ι Iota	ρ Rho
β Beta	κ Kappa	σ Sigma
γ Gamma	λ Lambda	τ Tau
δ Delta	μ Mu	υ Upsilon
ϵ Epsilon	ν Nu	ϕ Phi
ζ Zeta	ξ Xi	χ Chi
η Eta	o Omicron	ψ Psi
θ Theta	π Pi	ω Omega

Star Magnitudes. The Greek astronomers divided the naked-eye stars into six *magnitudes*, according to the apparent brightness. The brightest stars were listed as "first magnitude" stars, and those barely visible to the naked eye on the best nights were listed as "sixth magnitude." In more modern times, after the development of photometry, it was found that the average first-magnitude star gave just about 100 times as much light as the average sixth-magnitude star. It was decided, therefore, to make this difference of five magnitudes, or any difference of five magnitudes, equal to a brightness ratio of exactly 100. This meant that other magnitude differences would be indicated by the following approximate table.

TABLE II

Magnitude Difference	*Brightness Ratio*
One	2 1/2
Two	6 1/4
Three	16
Four	40
Five	100
Ten	10,000
Fifteen	1,000,000
Twenty	100,000,000

There is a physiological law which states that the intensity of a light source must be increased by a geometrical ratio (multiplying), to have the eye record the increase as an arithmetical ratio (adding). Photographic film is similar to the eye, and the change

in exposure with different stops and different conditions should be made by multiplying or dividing. This law explains the preceding tables.

Since brightness ratios are obtained by multiplying, the brightness ratio for a difference of six magnitudes $(6 = 5 + 1)$ can be obtained by multiplying the brightness ratio for a difference of five magnitudes (100) by the ratio for a difference of one magnitude (2 1/2). The result is 250. The brightness ratio for a difference of 13 magnitudes $(13 = 10 + 3)$, can be obtained by multiplying the ratio for a difference of 10 magnitudes by the ratio for a difference of three magnitudes. The result is 160,000; that is, a star of magnitude 0 gives as much light as 160,000 stars of magnitude 13, or any star gives as much light as 160,000 stars 13 magnitudes fainter.

To express magnitude differences more accurately, consider two stars of magnitude m and n respectively. Denote the brightness ratio for two successive magnitudes (approximately 2 1/2) by ρ, and let the brightness of one star be lm, and the brightness of the other be ln. Then, from the preceding laws their brightness ratio is

$$lm/ln = \rho\ (n - m).$$

Taking logarithms

$$\log lm/ln = (n - m) \log \rho.$$

But $\rho = \sqrt[5]{100}$, and $\log \rho = 0.4$, exactly. Hence,

$$\log (lm/ln) = 0.4\ (n - m)$$

or

$$n - m = 2.5 \log lm/ln = 2.5\ (\log lm - \log ln).$$

If the light of two stars is measured with an accurate photometer, in any units, the magnitude difference can be calculated from the preceding equation.

Colors of Stars. All stars are exceedingly hot, but some are much hotter than others. The hotter the filament of an electric light bulb is, the bluer it appears; and the hotter a star is, the bluer it appears. The following is a list of bright stars in order of color, beginning with the cooler, or reddish stars.

Red	Betelgeuse, Antares
Reddish	Aldebaran
Orange	Arcturus, Pollux
Yellow	The Sun, Capella
Yellowish	Procyon
Bluish	Altair
Blue	Sirius, Vega, Rigel

On any good night when several of the above stars are visible it will be found interesting to check on the color. It is easy to see that Betelgeuse is a deeper red than Aldebaran, for example, and that Rigel is a deeper blue than Procyon.

The Brightest Stars. The following table lists the twenty brightest stars. They are called the "first-magnitude" stars, although modern observers, using photometers, have found it necessary to use negative magnitudes for the brightest.

TABLE III

Name	*Magnitude*
Sirius	−1.58
Canopus[1]	−0.86
Rigil Kentaurus[1]	+0.06
Vega	0.14
Capella	0.21
Arcturus	0.24
Rigel	0.34
Procyon	0.48
Achernar[1]	0.60
Beta Centauri[1]	0.86
Altair	0.89
Betelgeuse	0.92
Acrux[1]	1.05
Aldebaran	1.06
Pollux	1.21
Spica	1.21
Antares	1.22
Fomalhaut	1.29
Deneb	1.33
Regulus	+1.34

[1] Not visible in latitude 40° N.

Magnitudes can be determined for any source of light, as for example, for the planets, the Moon, and the Sun. For the planet Jupiter, the magnitude is -2; for the planet Venus, the magnitude is -4; for the full Moon, the magnitude is -12; and for the Sun the magnitude is -26.

Dating the Constellations. The earliest complete list of the known constellations is given in the poem of Aratus of Soli, *The Phenomena,* published about 270 B.C. Forty-eight constellations are listed in this early Greek poem, but since the constellation figures are older than our recorded history, it is necessary to date their origin from the figures themselves.

Let us suppose that on a celestial globe one eliminates, or covers, all the star figures except the original 48. When this is done, it is evident that the early constellations covered the heavens with the exception of a large, approximately circular, area in the south. Presumably no constellations were named in this area because this area could not be seen at the time of naming. Calculation shows that the south pole of the heavens was the center of this circular area about 2700 B.C. From the diameter of this circular area it would have been the area invisible to people living between 36° and 40° north latitude.

Several lines of evidence agree in indicating that the constellations were laid out about 2700 B.C. by people living somewhere between 36° and 40° north latitude. To fix the longitude, let us consider the animals pictured. Surely we can assume that people would picture in the sky the animals with which they were familiar.

The ancient Egyptian civilization is ruled out because Egypt is too far south (south of 36° to 40° north latitude). The southern European countries, southern Greece, southern Spain, and southern Italy are within the correct latitudes, but they cannot be considered because they do not have the lion and the bear, which are included in the sky picture. The animals pictured in the constellations were familiar to people living in Asia Minor, Assyria, or Mesopotamia, between 36° and 40° north latitude. Probably the constellations were laid out by people living in the northern portion of what is now Turkey.

Learning the Constellations. To learn the constellations the essentials are first, a set of star charts showing the chief configurations, and second, outdoor study of the configurations as they

appear in the sky at different times of the night and of the year. A flashlight, so that the star charts can be read at night well away from other lights, is a convenience. The flashlight should be of the focusing type so that the beam can be used as a pointer in following the configurations in the sky. The use of the star charts and the study of the stars in the sky should be carried on together. Those who depend on the pointing out by a friend or teacher find themselves in difficulty when the stars are in a different position if they are unable to use a star chart to check on the appearance.

Directions in the Sky. Students learning the constellations for the first time often use directions with respect to terrestrial objects, and also up and down, in locating the constellations. This causes difficulty when the stars are in a different position, so the con-

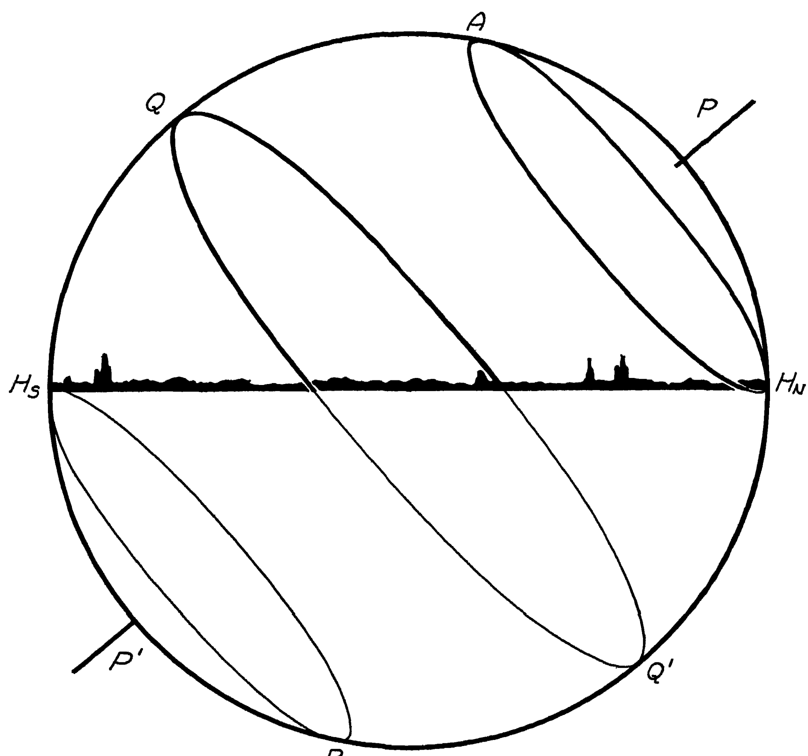


FIG. 7. The Limiting Diurnal Circles of Stars at 40° N. Latitude

stellation figures should be learned with respect to the stars, by forming lines, triangles, and other figures.

North, in the sky, is toward the north celestial pole, or approximately toward Polaris. North of the Big Dipper, for example, is downward when that constellation is above Polaris, and upward when that constellation is below Polaris. East is the direction from which the stars appear to move as they cross the sky. A star which is east of another appears to be "following" the other. South is the direction opposite to north, of course, and west is the direction opposite to east.

The apparent paths of the stars as they move across the celestial sphere are called diurnal circles. The position of the celestial sphere with respect to the visible horizon, for a person at approximately 40° N. latitude, is illustrated in Fig. 7. The north-celestial pole is at P and the celestial equator is QQ'. The stars between A and H_n can always be seen circling around the pole. The stars between Q and A are above the horizon longer than below. Those right on QQ' are, of course, above the horizon just as long as they are below. Those between Q and H_s are below the horizon longer than they are above it, and those between H_s and B are never seen at latitude 40° N.

The Constellation Figures. A casual glance at the evening sky shows that the stars, instead of being scattered at random, are arranged in groups, or configurations. There are right, isosceles, and equilateral triangles, parallelograms, and other easily recognized figures. Early people noticed these groupings, and assigned names to them, chiefly of their gods, heroes, and various animals. There are 48 constellation names which have come down to us from the ancients. Others have been added at various times, and at present 88 constellations are recognized by astronomers.

Groups of Constellations. Several sky pictures, or obvious groups, include two or more constellations. Among the better known are the following:

The Andromeda Picture. The Andromeda sky picture includes six constellations: Cassiopeia, the queen; Cepheus, the king; Andromeda, the daughter; Perseus, the hero; Pegasus, the flying horse; and Cetus, the sea monster.

The Hunting Picture. This picture includes five constellations: Orion, the Hunter; his two dogs, Canis Major, the Great Dog, and

Canis Minor, the Little Dog; Taurus, the Bull; and Lepus, the Rabbit.

The sky picture shows Orion, the mighty hunter, with his club raised as he is facing the charging bull. Behind him are his two dogs and at his feet is the rabbit.

In the days of the old Greek and Roman civilization it was noticed that the hot sultry weather of July and August occurred when the Sun was passing the *dog stars*, Sirius and Procyon. People suspected that the rays of these brilliant stars, added to the Sun's rays, increased the heat and were responsible for the hot weather at that time. Hence, this period of hot weather came to be known as *dog days*. The period is usually considered as beginning in the middle or latter part of July, with the ending in late August or early September. Notice that the *dog days* are so named because the Sun is passing the *dog stars*, not because the dog stars are conspicuous at that time. This is just the time of the year when the dog stars cannot be seen.

The Physician and the Serpent. The constellation picture shows a giant physician, Ophiuchus, holding a serpent, Serpens. Ever since early times, the serpent, or snake, has been connected with the medical profession in symbolism. The sign of the god Mercury, a winged staff with two serpents coiled about it, is called the Caduceus. Medical officers in the army wear the Caduceus to indicate their line of service, and many doctors attach the Caduceus to their cars.

The Flood Picture. There are seven constellations in the flood picture. They are: Argo, the Ark; Corvus, the Raven; Hydra, a Sea Serpent; Centaurus, the Noah of the old flood story; Ara, the Altar; Lupus, an animal being placed on the Altar; and Sagittarius, the archer whose Bow appears in the cloud.

As a result of precession (to be explained later) the position of this picture has changed greatly in the more than 4000 years since the naming of the constellations. In the United States, we can see Corvus, the Raven; Sagittarius, the Archer; and Hydra, the Sea Serpent. In most of the United States we can see only a little of the ship Argo and of Noah, the Centaur. Precession has moved the picture too far south.

The Zodiac. Early people noticed that the Moon and the planets were practically always within a band extending eight degrees on

each side of the ecliptic. The band, divided into twelve constellations corresponding to the twelve months of the year, was called the *zodiac.*

The twelve constellations of the zodiac are, in order beginning with the one containing the spring equinox: Pisces, the Fishes; Aries, the Ram; Taurus, the Bull; Gemini, the Twins; Cancer, the Crab; Leo, the Lion; Virgo, the Virgin; Libra, the Balance; Scorpio, the Scorpion; Sagittarius, the Archer; Capricornus, the Water Goat; Aquarius, the Water Bearer. In classical times the vernal equinox was in Aries, the Ram. In the days of the Pyramids the vernal equinox was in Taurus, the Bull. This change is due to precession of the equinoxes, discussed in Chapter V.

The so-called "signs of the zodiac," used chiefly by astrologers, retain the order of classical times since that is the period in which astrology was developed, and the "signs" do not agree with the constellations. When the Sun is in the so-called sign of Aries, it is really among the stars forming the constellation Pisces. When it is in the so-called sign of Scorpio, the Scorpion, it is among the stars of the constellation Libra, the Balance. Each "sign" contains the stars of the constellation preceding it in the list.

Notes on the Constellations

The star names are listed under the constellations to which they belong, with these constellations in alphabetical order. The Greek letter name of each star is given, so that it can be identified on a star chart. The brighter star clusters, and other objects of special interest, are included in these notes. Each of these constellations is shown on the star chart indicated and all of them will be found in the Navigational Star Chart at the end of the *American Air Almanac.*

Andromeda. *Alpheratz* is Alpha. Alpheratz forms one corner of the "Square of Pegasus." The chief configuration in Andromeda is a line of stars running from the Square of Pegasus to Perseus. The only galaxy even faintly visible to the naked eye is known as the "Great Nebula in Andromeda" because it is in this constellation. The location is shown on Maps 3 and 9.

Aquila. *Altair* is Alpha. It is the central star of a line of three stars which points approximately toward Vega in Lyra, and if

extended the other way, toward Alpha in Capricornus as shown in Fig. 10, page 28. This constellation is shown on Maps 10 and 12.

Aries. *Hamal* is Alpha. This is a small configuration, three stars making a small obtuse triangle, and can be found on Maps 2, 3, and 12.

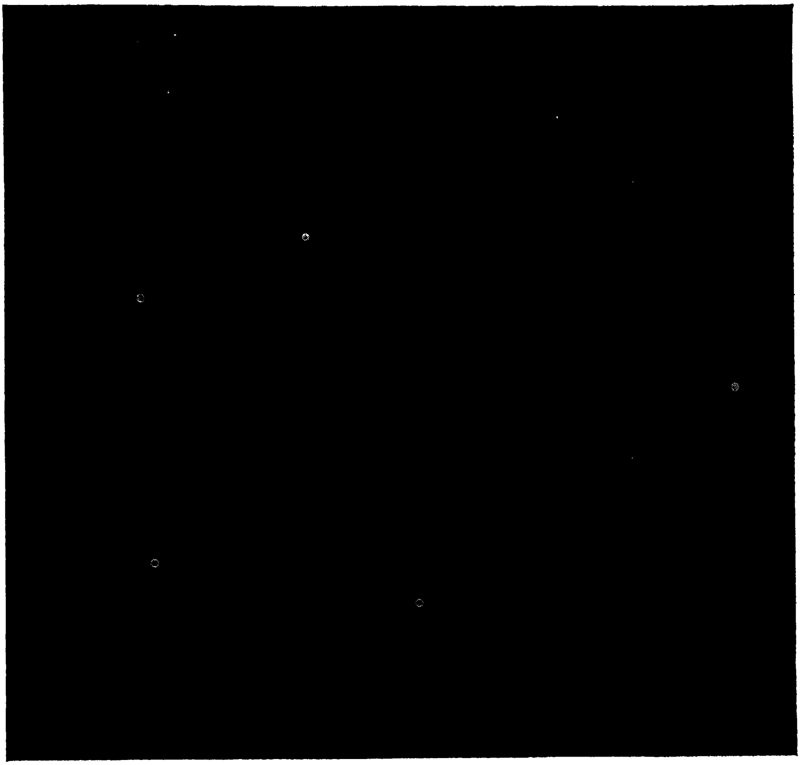


FIG. 8. The Constellation Auriga. Photograph from Yerkes Observatory and University of Chicago Press

Argo. *Canopus* is Alpha, and *Miaplacidus* is Beta. This is a huge constellation lying to the south and east of the dog stars. The brightest stars are not visible from latitude 40° north. Canopus is the second brightest star in the heavens, outshining all others but Sirius. Argo is shown on Map 14.

Auriga. *Capella* is Alpha. It is the second brightest star north of the celestial equator, the brightest being Vega in Lyra. Capella is identified by the little isosceles triangle of fainter stars beside it

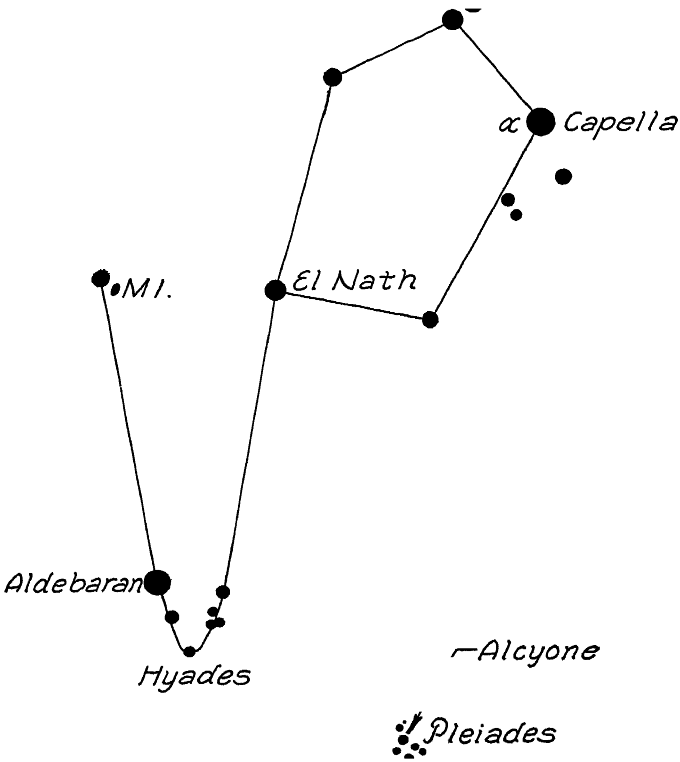


FIG. 9. The Constellations Taurus and Auriga

and can be found on Maps 5 and 11. Auriga borrows one of Taurus' horns to complete the pentagon as shown in Fig. 9.

Boötes. *Arcturus* is Alpha. It is the third brightest star north of the celestial equator. The brightest star is Vega in Lyra, and the second brightest is Capella in Auriga. Arcturus is a reddish star and is found readily by extending the curve of the handle of the Big Dipper as indicated in Fig. 14, page 33. This constellation is shown on Maps 5, 6, and 8.

Cancer. *Praesepe,* a cluster, is the distinctive object in this constellation. Praesepe, also called the "Beehive," is a ball of haze to the naked eye, and the two stars beside it give it a distinctive appearance. On clear moonless nights it is found readily by looking near the middle of a line extended from Castor and Pollux in Gemini to Regulus in Leo. The Tropic of Cancer is named after this constellation. The location of Praesepe is shown on Maps 4 and 6.

Canes Venatici. *Cor Caroli* is Alpha. This is one of the most modern constellations, having been formed by Hevelius in the seventeenth century. It is shown on Map 7.

Canis Major. *Sirius* is Alpha. This star (the brighter "Dog Star") is the most brilliant in the heavens, is one of the bluest and hottest visible to the naked eye, and is the nearest seen with the naked eye from as far north as latitude 40°. It is shown on Maps 2 and 4.

Canis Minor. *Procyon* is Alpha. It is the lesser "Dog Star," and it can be located on Maps 2, 4, and 6.

Capricornus. This constellation has no bright stars, but Alpha, which appears as a naked-eye double, and Beta nearby form a distinctive configuration. It is found readily by extending a line from the bright Vega in Lyra through Altair in Aquila as indicated in Fig. 10, page 28. The Tropic of Capricorn is named after this constellation. This constellation is shown on Maps 10 and 12.

Cassiopeia. This constellation is marked by a sprawling capital *W* configuration and has no distinctively bright stars. It lies on the opposite side of Polaris from the handle of the Big Dipper and at nearly the same distance, and it is shown on Maps 1, 3, 5, 7, 9, 11, and 13.

Cepheus. This constellation contains no bright stars. Some see in Cepheus a sprawling capital *K*, but others find it easier to see a church spire, the configuration marked on the map. The easiest way to find this constellation is to remember that it goes around the pole star just ahead of Cassiopeia, and consequently can be found on the same charts as those given in the preceding paragraph.

Cetus. *Deneb Kaitos* is Beta, and it can be located on Maps 2 and 12.

Coma Berenices. The only noticeable feature of this constellation

is an open cluster, composed of a great number of relatively faint stars. It can be located on Maps 6 and 8 and is easily found in the sky halfway between Cor Caroli and Denebola.

Corona Borealis. *Alphecca* is Alpha. This constellation is a semicircle of stars always open to the north and is shown on Maps 5, 8, and 10.

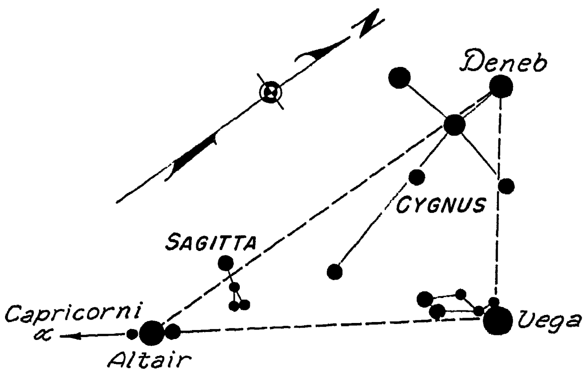


FIG. 10. The Right Triangle

Cygnus. *Deneb* is Alpha. This constellation is known also as the Northern Cross, since the configuration which marks it is a cross. It is shown on Maps 1, 7, and 11.

Crux. *Acrux* is Alpha. This constellation, the Southern Cross, is the best known of those not visible from latitude 40° north. It is shown on Map 14.

Draco. *Thuban* is Alpha. This is not a bright star, or even the brightest in the constellation, but it is famous because it was the pole star in the days of the Pyramids. It is found almost at the halfway point on a line between Mizar in the Big Dipper and Kochab in the Little Dipper, and the constellation can be located on Maps 1, 3, 5, 7, 9, 11, and 13.

Eridanus. *Achernar* is Alpha. This is a long line of stars, supposed to represent a river, running from beside Rigel, in Orion, to below the southern horizon for latitude 40° north. Achernar is the southernmost and is not visible in that latitude. This constellation can be found on Maps 2, 4, and 14.

Gemini. *Castor* is Alpha, and *Pollux* is Beta. Pollux is the brighter star, but the Twins were spoken of as Castor and Pollux, so the

Greek letters were assigned in that order. Castor is the one closer to Polaris.

Castor and Pollux, the Twins, were considered the special gods of sailors in classical times. In those days people often swore by the gods, and a common oath was "By Gemini." This oath has survived to modern times in the corrupted form "By Jimminy." Gemini is shown on Maps 1, 4, and 5.

Hercules. There are no bright stars in this constellation. The most conspicuous configuration for many is a sort of butterfly figure, which is shown on Maps 5, 8, 10, and 11.

People always have enjoyed imaginative stories in which the hero had prodigious strength, could fly through the air like a bird, and was practically immune to the weapons ordinarily used. In modern stories, the hero usually obtains his great strength and immunity by being the product of another and more advanced planet, or by taking some miraculous vitamin or drug prepared by a super-scientist. The hero, Hercules, was the supernaturally strong man in the stories of early Greece. He, like most other Greek heroes, obtained his great strength from the fact that he was the son of Jupiter, the King of the Gods. In other words, he was half-god and half-human. He obtained his immunity to weapons by carrying a lion skin which could not be penetrated by the swords, spears, and arrows of his time.

Hydra. *Alphard* is Alpha. This is the longest constellation in the sky, a line of relatively faint stars, most of them rather low in the south for latitude 40° north. It is shown on Maps 4 and 6.

Leo. *Regulus* is Alpha and *Denebola* is Beta. This constellation includes two conspicuous configurations, the Sickle, with Regulus

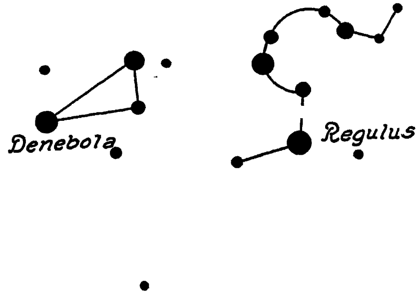


FIG. 11. The Constellation Leo

in the handle, and a nearly right triangle with Denebola at the smallest angle as indicated in Fig. 11. Leo is shown on Maps 4 and 6.

Lyra. *Vega* is Alpha. This small constellation includes an equilateral triangle and parallelogram, all of the stars excepting Vega being relatively faint. Vega is the brightest star north of the celestial equator. Vega, Deneb in Cygnus, and Altair in Aquila, make a big and conspicuous right triangle with Vega at the right angle as shown in Fig. 10. Lyra can be located on Maps 7, 10, and 11.

Orion. *Betelgeuse* (or Betelgeux) is Alpha, *Rigel* is Beta, *Bellatrix* is Gamma, and *Saiph* is Kappa. This constellation, including

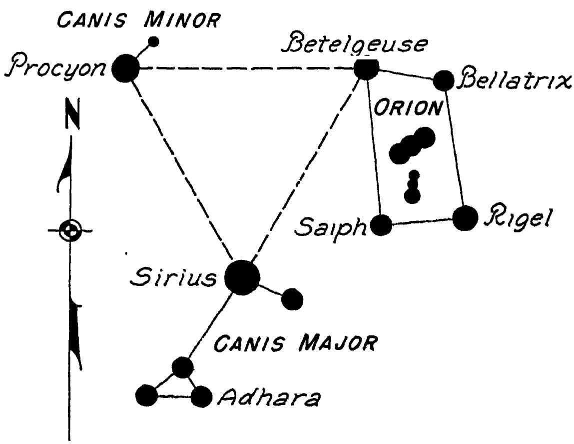


FIG. 12. The Equilateral Triangle

many bright stars, is considered the finest in the sky by many people. The three stars in the belt point approximately toward the bright dog star Sirius. Betelgeuse, Sirius in Canis Major, and Procyon in Canis Minor, make a big equilateral triangle which is illustrated in Fig. 12. Orion is shown on Maps 2 and 4.

Pavo. *Peacock* is Alpha. This is a southern constellation, not visible in latitude 40° north. Peacock, about as bright as Polaris, is the only star noticeable on an ordinary night in this constellation and can be found on Map 14.

Pegasus. *Markab* is Alpha. This constellation is marked by a great square composed of Alpheratz in Andromeda and three stars

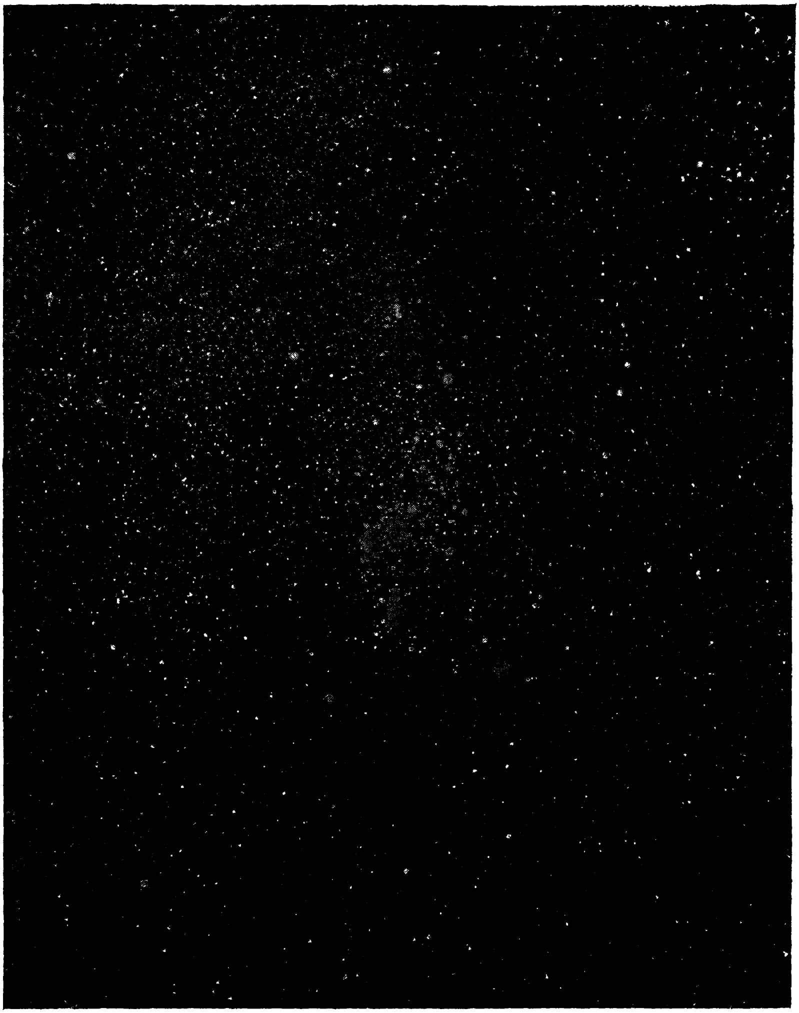


FIG. 13. The Constellation Orion. Photographed December 21, 1919, at Mount Wilson Observatory

in Pegasus, Beta, Markab, and Gamma. Pegasus and Andromeda taken together make a conspicuous and easily recognized configuration. Pegasus is shown on Maps 2 and 12.

Perseus. *Marfak* is Alpha and *Algol* is Beta. Perhaps the easiest configuration to see in Perseus is a "script A." Marfak is on a line

with the chief stars of Andromeda, Alpheratz, Beta, and Gamma. Perseus is located on Maps 1, 3, and 11.

Piscis Austrinus (or Piscis Australis). *Fomalhaut* is Alpha. This star is the only one in the constellation seen readily on an average night and can be found on Maps 10 and 11.

Sagittarius. This constellation is marked by a small dipper-shaped figure, with the dipper inverted and the handle to the west. This is called the "Milk Maid's Dipper." The central star clouds of our galaxy are in this constellation. Sagittarius is shown on Map 10.

Scorpio. *Antares* is Alpha. This constellation originally included Libra, the two principal stars of that constellation marking the claws of the Scorpion. Antares is a brilliant red star. This constellation can be found on Maps 8 and 10.

Taurus. *Aldebaran* is Alpha, and *Alcyone* is Eta. The *Hyades* is a V-shaped group marking the head of the Bull, with the bright reddish Aldebaran as the eye. On the shoulder of the Bull is a little dipper-shaped cluster known as the *Pleiades*. Six stars are visible on an average clear night, and occasionally seven, or even more, can be seen. The brightest of the Pleiades is Alcyone. Taurus is shown on Maps 2 and 4, and its connection with Auriga is illustrated in Fig. 9, page 26.

Ursa Major. *Dubhe* is Alpha, *Merak* is Beta, *Mizar* is Zeta, and *Alcor* is a fainter star close to Mizar. The Big Dipper, a configuration which nearly everyone knows, is the conspicuous figure in this constellation. The two stars Dubhe and Merak, or Alpha and Beta, are known as the "Pointers," since they point toward Polaris, the North Star. Ursa Major and Ursa Minor can be found on Maps 1, 3, 5, 7, 9, 11, and 13.

Ursa Minor. *Polaris* is Alpha, and *Kochab* is Beta. The chief configuration in this constellation is the Little Dipper, with Polaris, the North Star or pole star, the star at the end of the handle and Kochab at the edge of the bowl.

Virgo. *Spica* is Alpha. It is found easily by extending the curve of the handle of the Big Dipper on through Arcturus in Boötes an equal distance to Spica as shown in Fig. 14. Spica, Denebola in Leo, Cor Caroli in Canes Venatici, and Arcturus in Boötes make a conspicuous great diamond in the sky. (See Fig. 14.) Virgo is located on Maps 6 and 8.

The Northern Circumpolar Constellations. Map 13 shows the

region of the heavens which is always above the horizon at 50° north latitude or farther north. These constellations circle about the celestial pole without going below the horizon, so they are

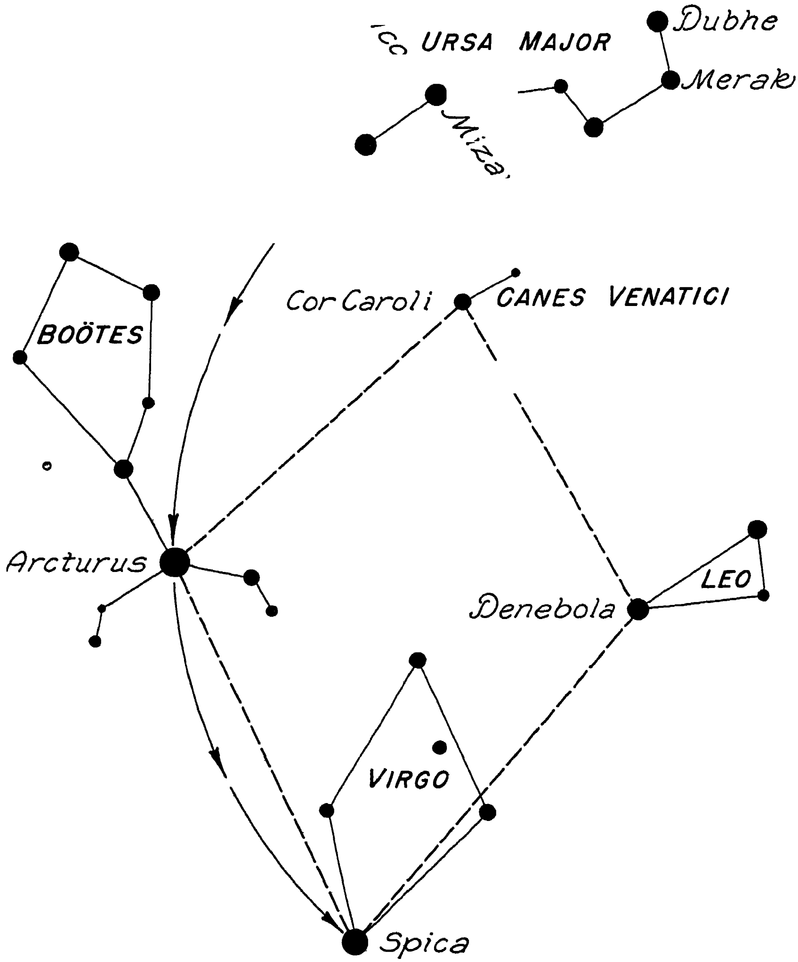


FIG. 14. The Great Diamond

called "circumpolar constellations." As they are visible on any clear night, it is well for students to learn them first, and use them as reference points in finding other constellations. If Map 13 is held

TABLE IV. CONSTELLATIONS AND IMPORTANT STARS[4]

Latin Name	*Genitive*	*English Name*	*Important Stars*	*Map No.*
Andromeda	Andromedae	Andromeda, the Maiden	Alpheratz[2]	3, 9, 12
Aquarius	Aquarii	Water Bearer		10, 12
Aquila	Aquilae	Eagle	Altair[2]	10, 12
Ara	Arae	Altar		14
Argo[3]	Argus	Ship	Canopus[2], Miaplacidus	14
Aries	Arietis	Ram	Hamal	2, 3, 12
Auriga	Aurigae	Charioteer	Capella[2]	5, 11
Boötes	Boötis	Boötes, the Bear Driver	Arcturus[2]	5, 6, 8
Cancer	Cancri	Crab		4, 6
Canes Venatici[1]	Canum Venaticorum	Hunting Dogs	Cor Caroli	7
Canis Major	Canis Majoris	Great Dog	Sirius[2]	2, 4
Canis Minor	Canis Minoris	Little Dog	Procyon[2]	2, 4, 6
Capricornus	Capricorni	Water Goat		10, 12
Cassiopeia	Cassiopeiae	Cassiopeia, the Queen		1, 3, 5, 7, 9, 11, 13
Centaurus	Centauri	Centaur	Rigil Kentaurus[2]	14
Cepheus	Cephei	Cepheus, the King		1, 3, 5, 7, 9, 11, 13
Cetus	Ceti	Cetus, the Sea Monster	Deneb Kaitos	2, 12
Columba[1]	Columbae	Dove		2, 4
Coma Berenices[1]	Comae Berenices	Berenice's Hair		6, 8
Corona Borealis	Coronae Borealis	Northern Crown		5, 8, 10
Corvus	Corvi	Raven		6, 8
Crater	Crateris	Cup		6, 8
Crux[1]	Crucis	Southern Cross	Acrux[2]	14
Cygnus	Cygni	Swan, or Northern Cross	Deneb[2]	1, 7, 11
Delphinus	Delphini	Dolphin, or Job's Coffin		10, 12
Draco	Draconis	Dragon	Thuban	1, 3, 5, 7, 9, 11, 13
Eridanus	Eridani	River	Achernar[2]	2, 4, 14
Gemini	Geminorum	Twins	Pollux[2], Castor	1, 4, 5
Grus[1]	Gruis	Crane		14
Hercules	Herculis	Hercules, the Hero		5, 8, 10, 11,
Hydra	Hydrae	Sea Serpent	Alphard	4, 6
Leo	Leonis	Lion	Regulus[2], Denebola	4, 6

Lepus	Leporis	Rabbit		2, 4
Libra	Librae	Balance		8, 10
Lupus	Lupi	Wolf		14
Lyra	Lyrae	Harp	Vega[2]	7, 10, 11
Ophiuchus	Ophiuchi	Ophiuchus, the Doctor		8, 10
Orion	Orionis	Orion, the Mighty Hunter	Rigel[2], Betelgeuse[2], Bellatrix, Saiph	2, 4
Pavo	Pavonis	Peacock	Peacock[2]	14
Pegasus	Pegasi	Pegasus, the Flying Horse	Markab	2, 12
Perseus	Persei	Perseus, the Hero	Marfak, Algol	1, 3, 11
Phoenix[1]	Phoenicis	Phoenix		14
Pisces	Piscium	Fishes		2, 12
Piscis Austrinus	Piscis Austrini	Southern Fish	Fomalhaut[2]	10, 12
Sagitta	Sagittae	Arrow		10
Sagittarius	Sagittarii	Archer		10
Scorpio, or Scorpius	Scorpionis, or Scorpii	Scorpion	Antares[2]	8, 10
Serpens	Serpentis	Serpent		8, 10
Taurus	Tauri	Bull	Aldebaran[2]	2, 4
Triangulum	Trianguli	Triangle		2, 3
Triangulum Australe[1]	Trianguli Australis	Southern Triangle		14
Ursa Major	Ursae Majoris	Great Bear	Dubhe[2], Merak, Mizar, Alcor	1, 3, 5, 7, 9, 11, 13
Ursa Minor	Ursae Minoris	Little Bear	Polaris[2], Kochab	1, 3, 5, 7, 9, 11, 13
Virgo	Virginis	Virgin	Spica[2]	6, 8

[1] Constellations added to the forty-eight constellations of classical times.

[2] The more important navigational stars. The student should be able to recognize any of the stars listed, even on a hazy night when only the brighter stars are visible.

[3] This constellation, which is very large, has been broken up into the parts of a ship by modern astronomers. The Latin names for these parts are Carina, Puppis, Pyxis, and Vela. The navigational chart, however, shows it as a single constellation.

[4] For pronunciations of these constellation and star names see page 441, in the Appendix.

up and to the north, with the name of the month at the top, it will show the constellations as they are at about nine o'clock in the evening.

The five circumpolar constellations for 40° to 50° north latitude are as follows: Ursa Major, the Great Bear; Ursa Minor, the Little Bear; Cassiopeia; Cepheus, and Draco, the Dragon. The constellations have been described, and the proper names of important stars given, in the preceding paragraphs under "Notes on the Constellations."

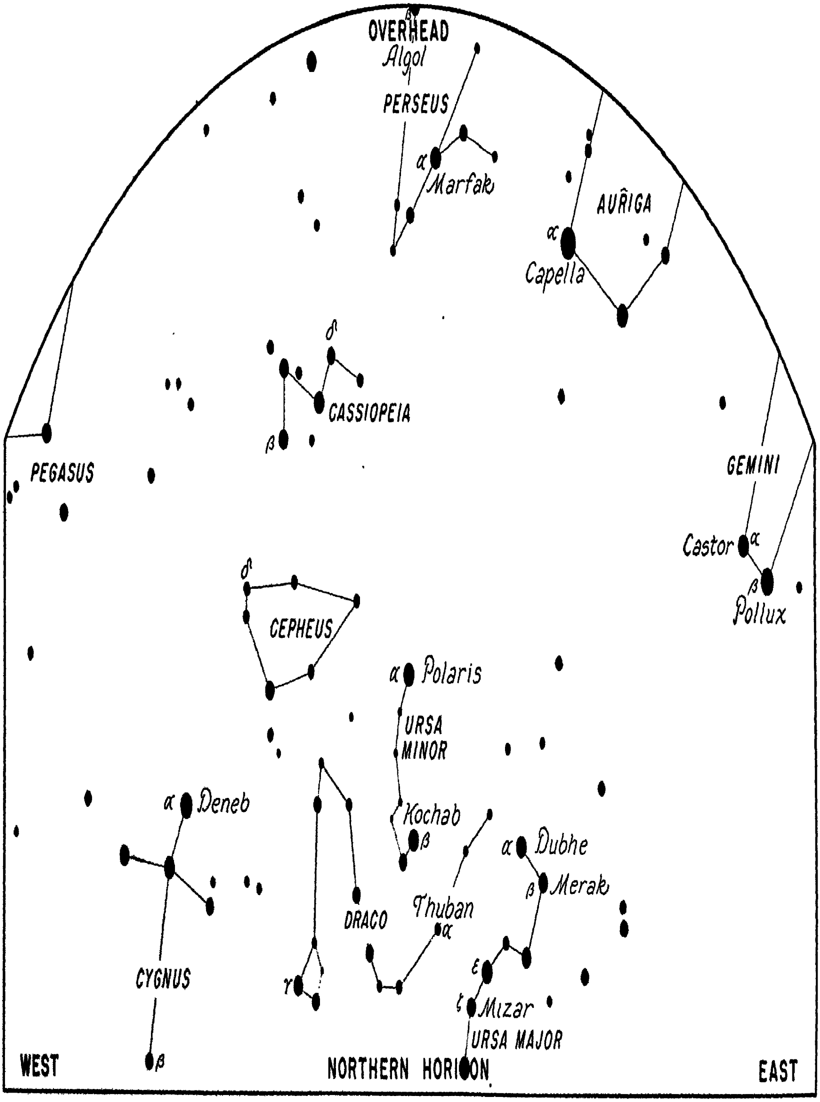
The Southern Circumpolar Constellations. Map 14 shows the region of the heavens which is always below the horizon at latitude 50° north, or farther north. It is always above the horizon at latitude 50° south, or farther south. Nine constellations are included, at least in part. They are as follows: Eridanus, with Achernar; Hydrus; Argo, with Canopus and Miaplacidus; Crux, with Acrux; Centaurus, with Rigil Kentaurus; Triangulum Australe; Ara; Pavo, with Peacock; and Grus.

The region of the south celestial pole is surrounded by faint stars, with nothing as bright as Polaris close enough to be of value in approximate work.

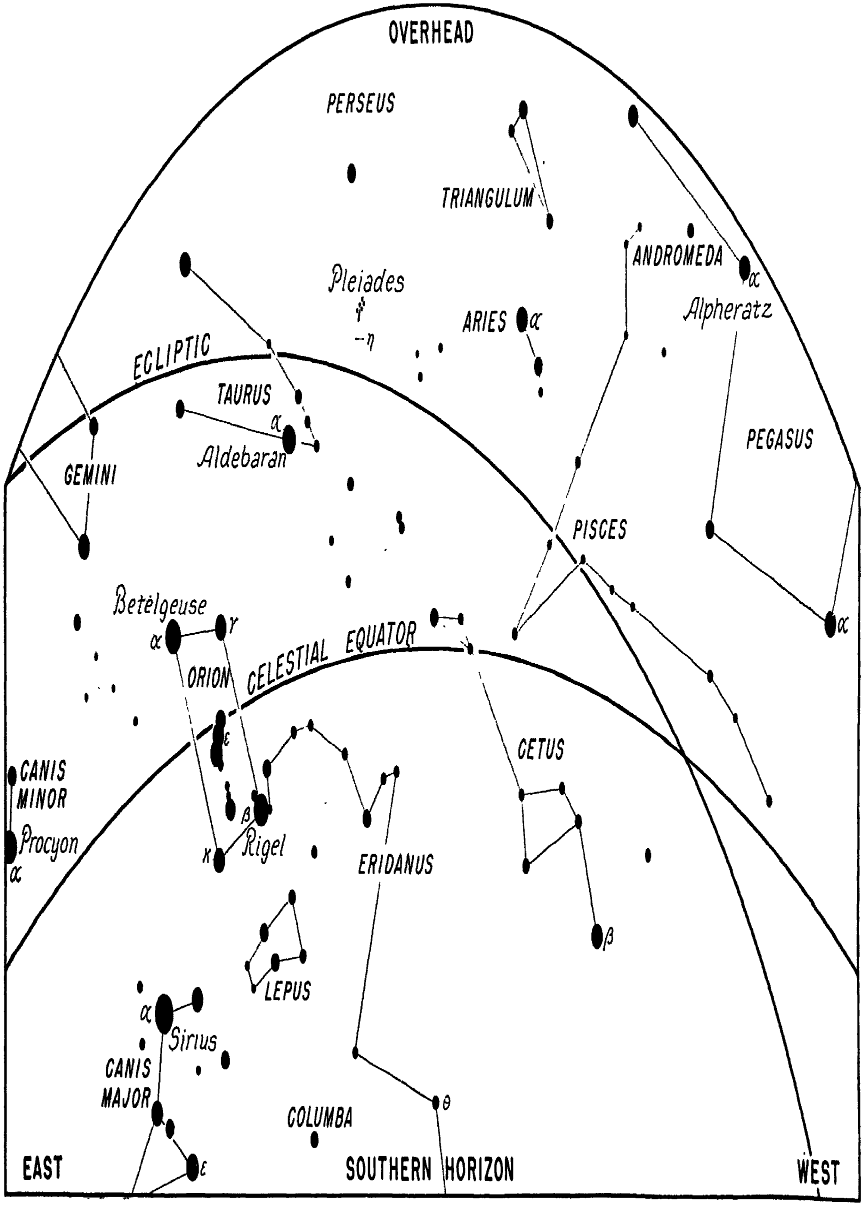
Exercises

1. How many stars can be seen at midnight by the average person;
   a. on a clear moonlight night?
   b. on a clear moonless night?
2. How many stars down to and including the sixth magnitude are there in the entire heavens?
3. Give three ways in which stars are designated, or named.
4. Memorize and be able to write the letters of the Greek alphabet.
5. What is meant by the magnitude of a star?
6. How much brighter is the light of the full moon (−12 magnitude) than that of Alcor (+4 magnitude)?
7. How many stars of the fifteenth magnitude would it take to equal Vega (0 magnitude) in brightness?
8. If a star is three times as bright as another, what is the approximate difference in their magnitudes?

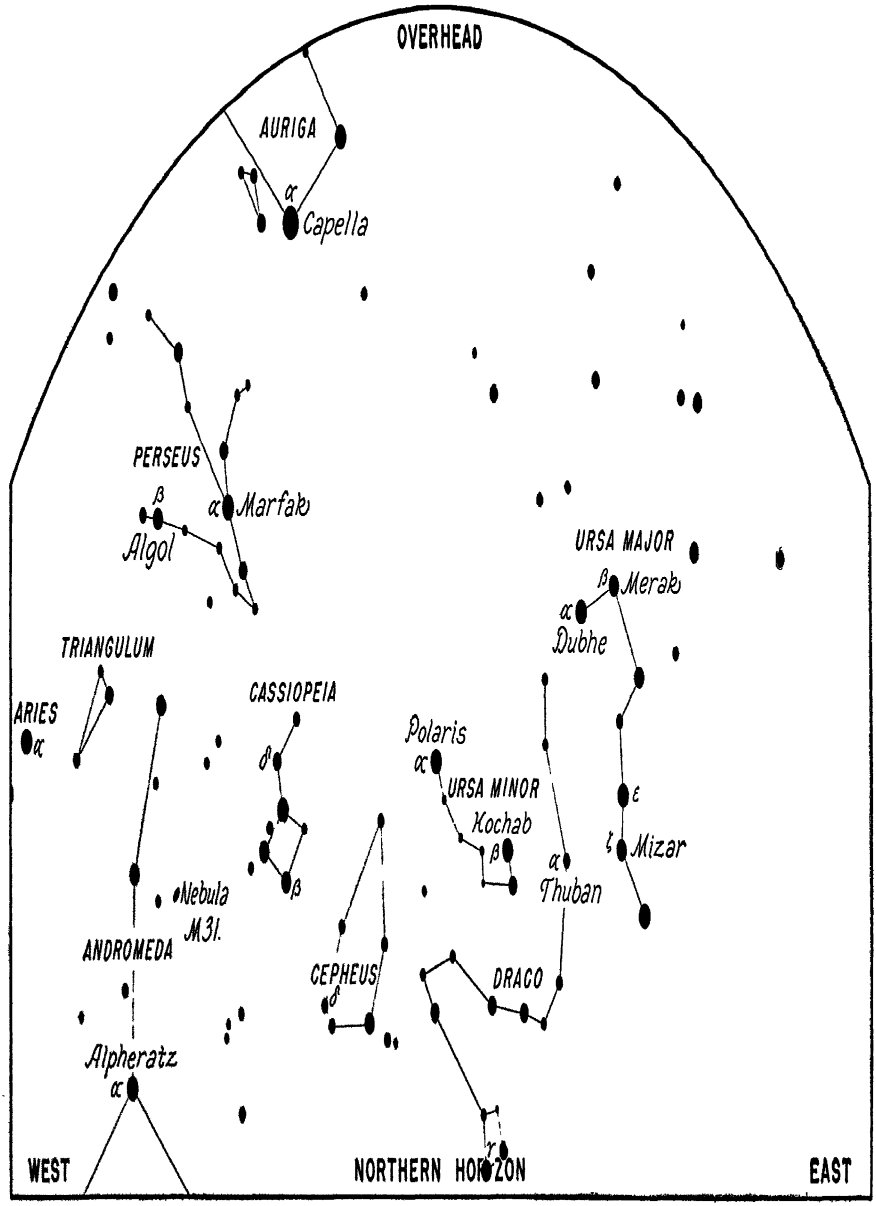
9. If Mars varies in a season from approximately 0 magnitude to magnitude +2, what is the change in apparent brightness?
10. One star is 100,000,000 times as bright as another. What is their difference in magnitude?
11. Name the so-called first-magnitude stars and give their constellations.
12. What constellations are on (a) the celestial equator; (b) the ecliptic, and (c) the zodiac? Which constellations are on all three?
13. Why do people in different latitudes see different circumpolar constellations? Where would one see no circumpolar constellations? Why?
14. What are some configurations involving stars in two or more constellations which help in identifying them?
15. Learn the important navigational stars, and their constellations, and be able to identify them quickly in the sky.



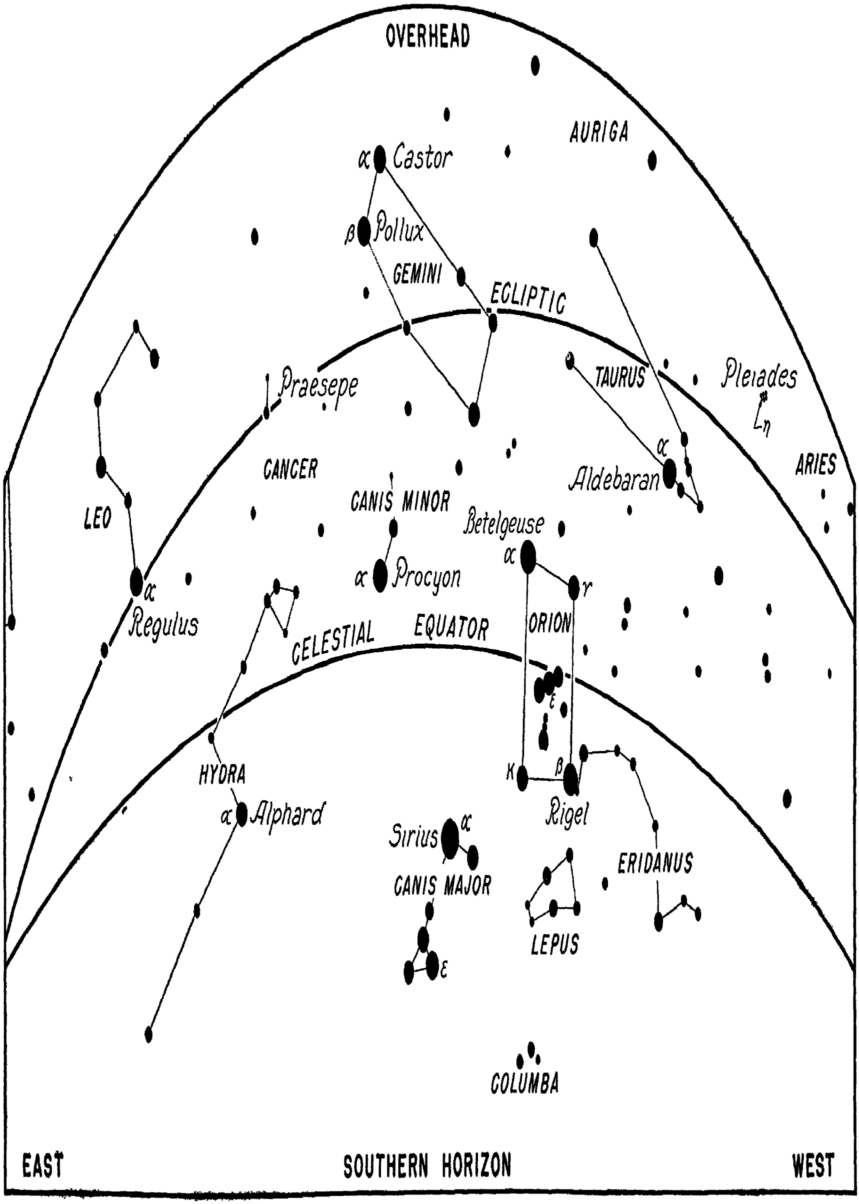
Map 1. The Northern Sky, 8:20 p.m., January 1



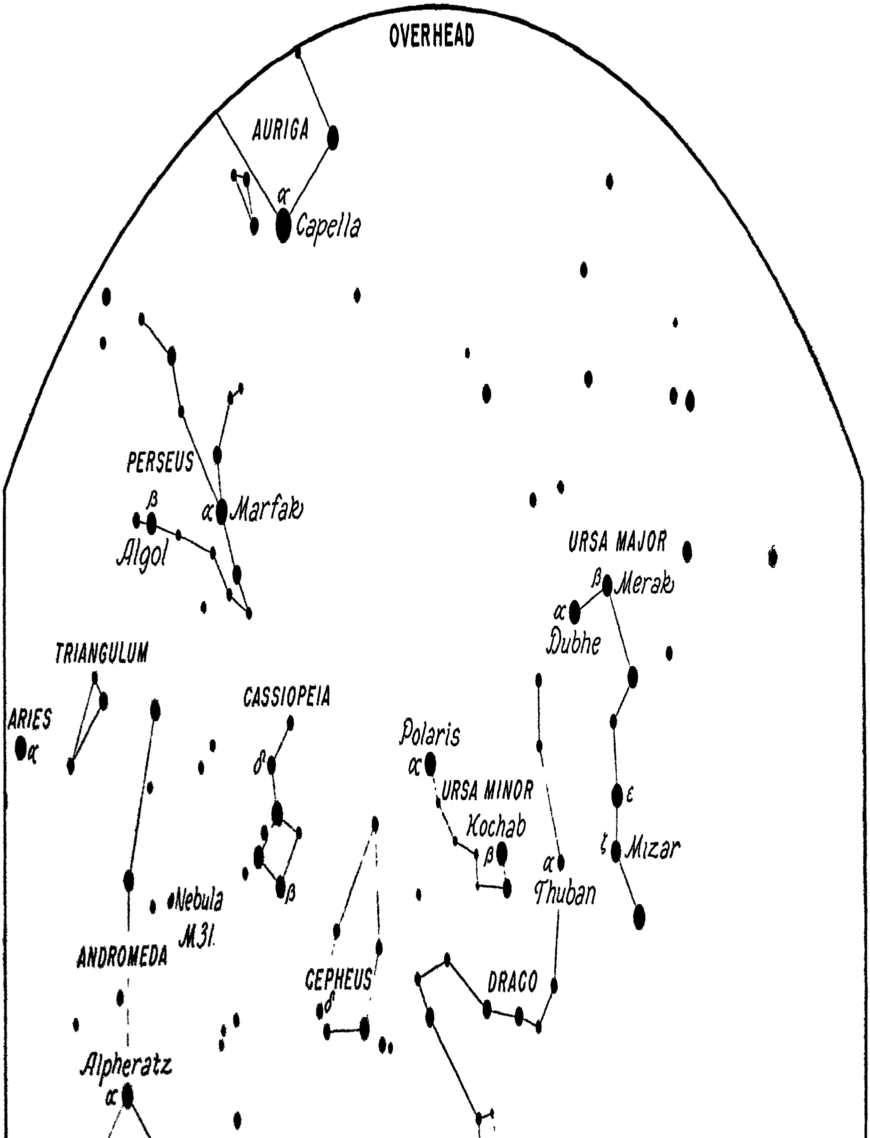
Map 2. The Southern Sky, 8:20 p.m., January 1



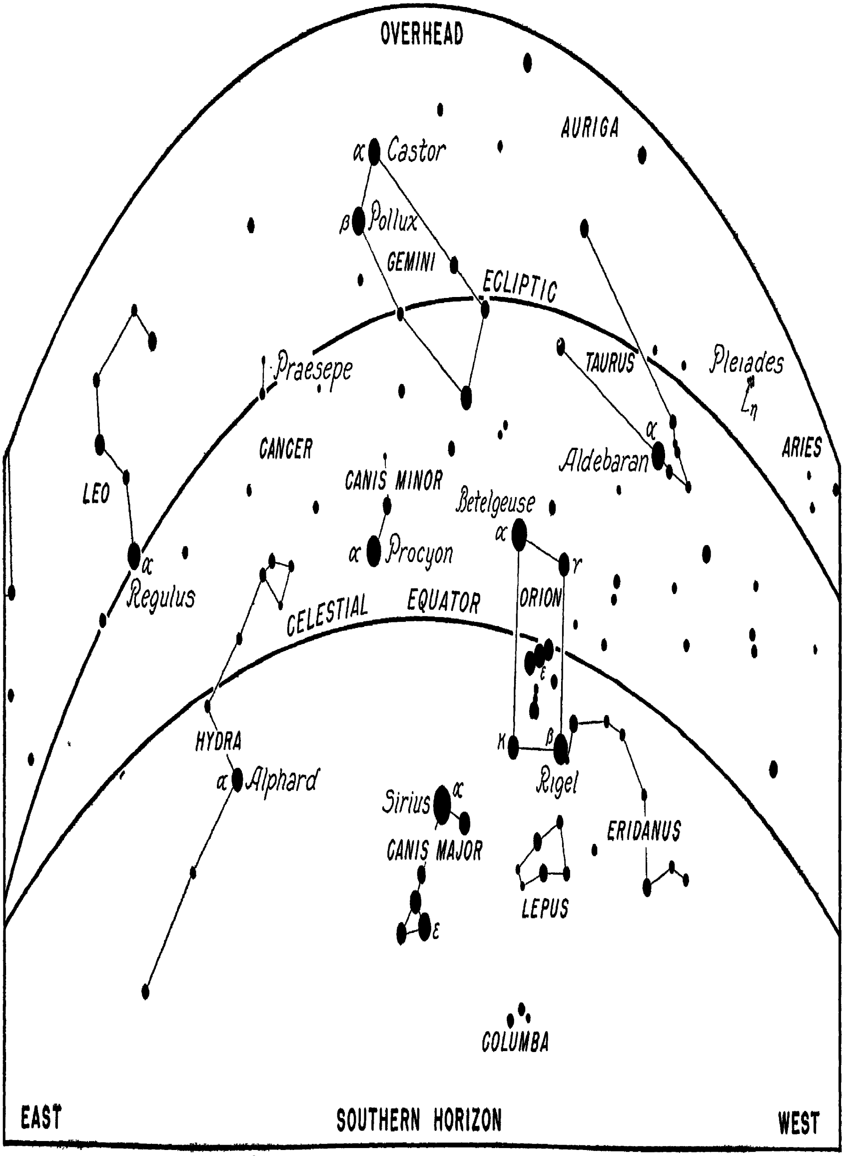
Map 3. The Northern Sky, 8:20 p.m., March 1



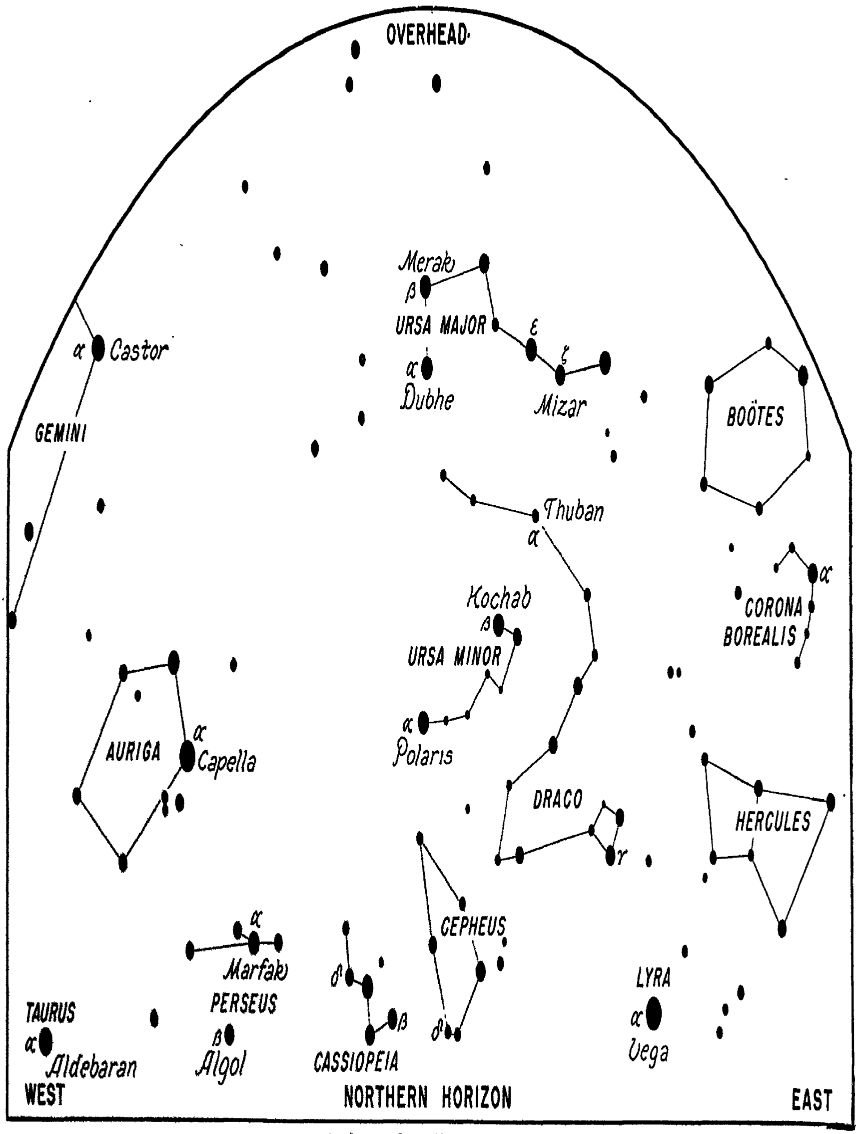
MAP 4. The Southern Sky, 8:20 p.m., March 1



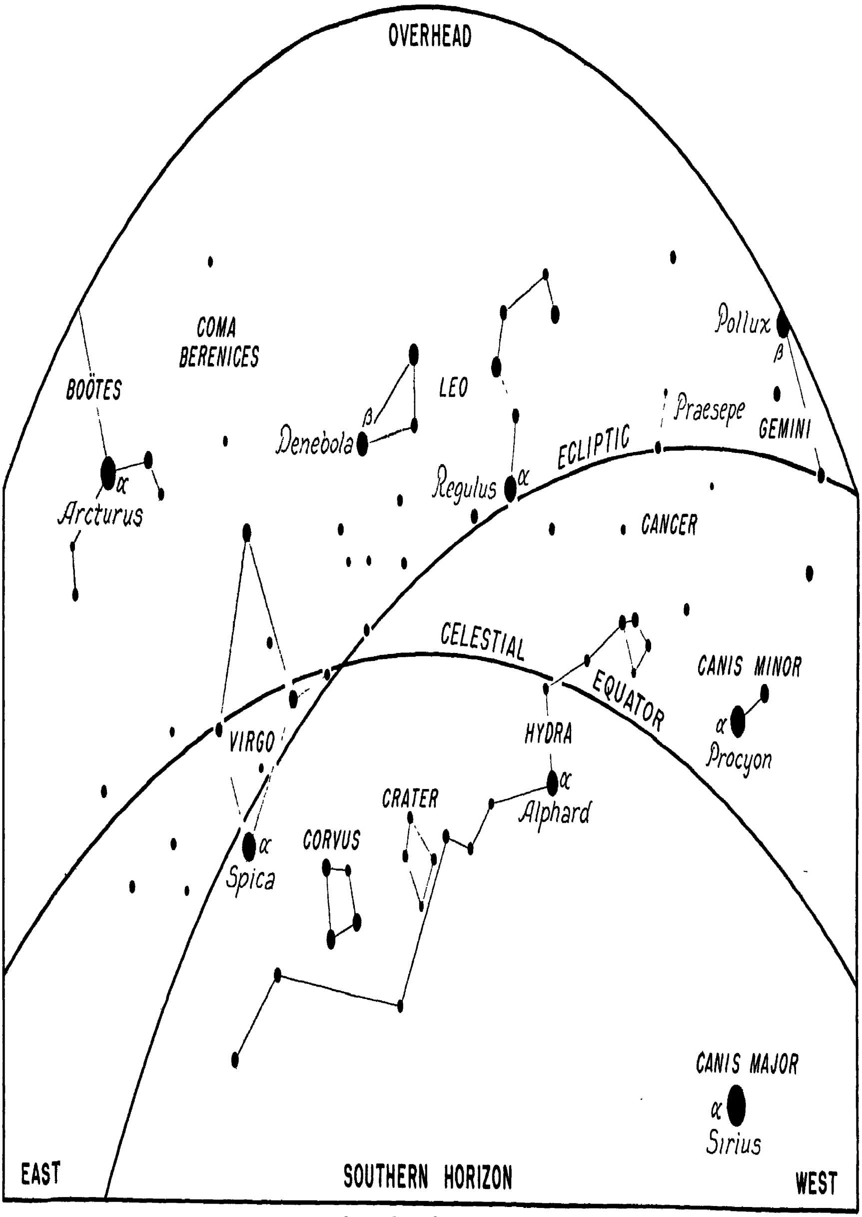
Map 3. The Northern Sky, 8:20 p.m., March 1



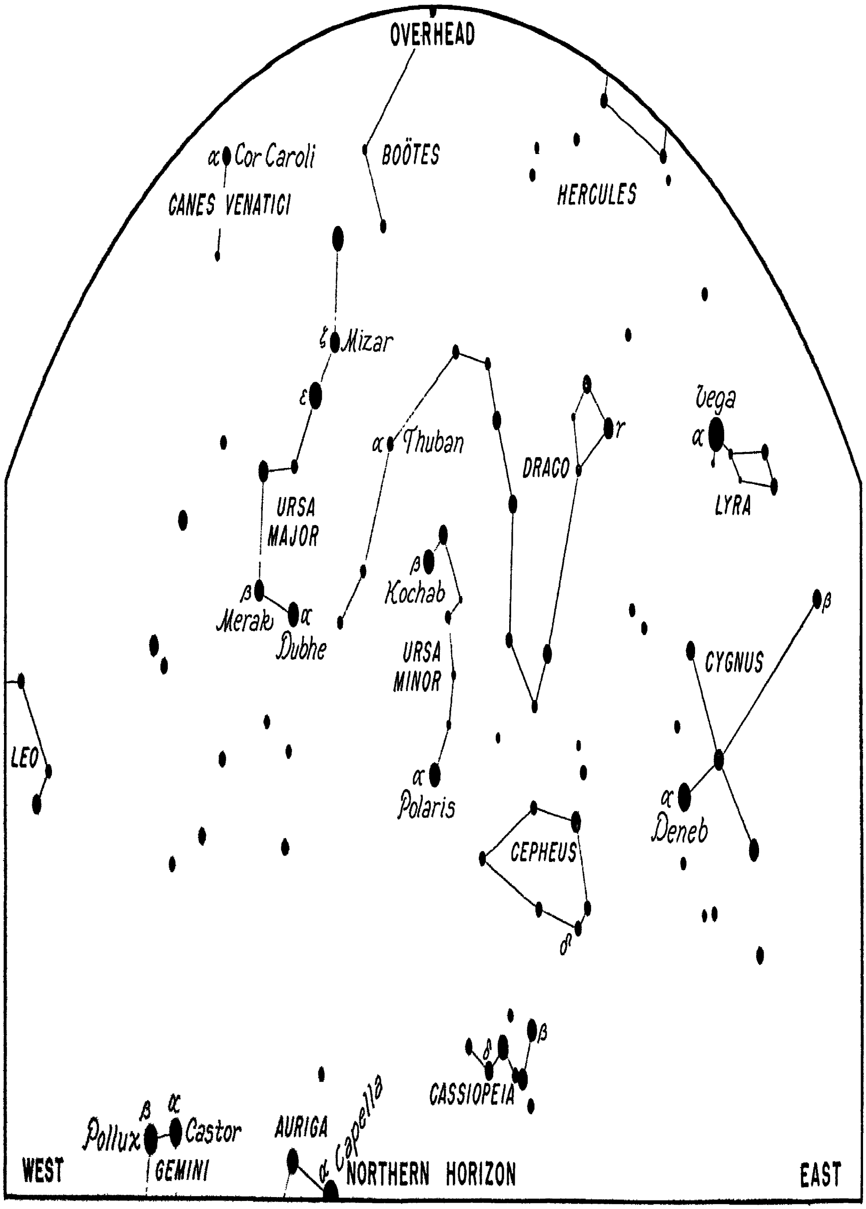
Map 4. The Southern Sky, 8:20 p.m., March 1



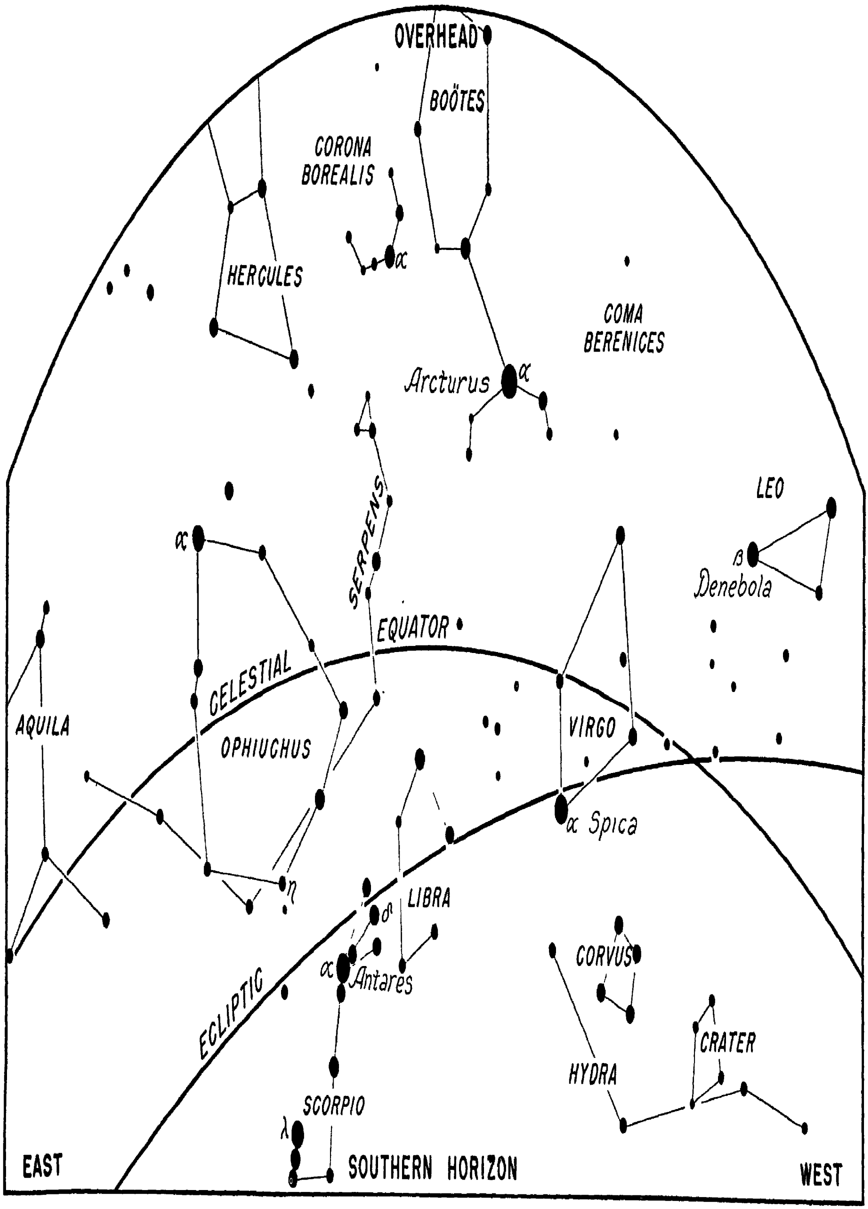
Map 5. The Northern Sky, 8:20 p.m., May 1



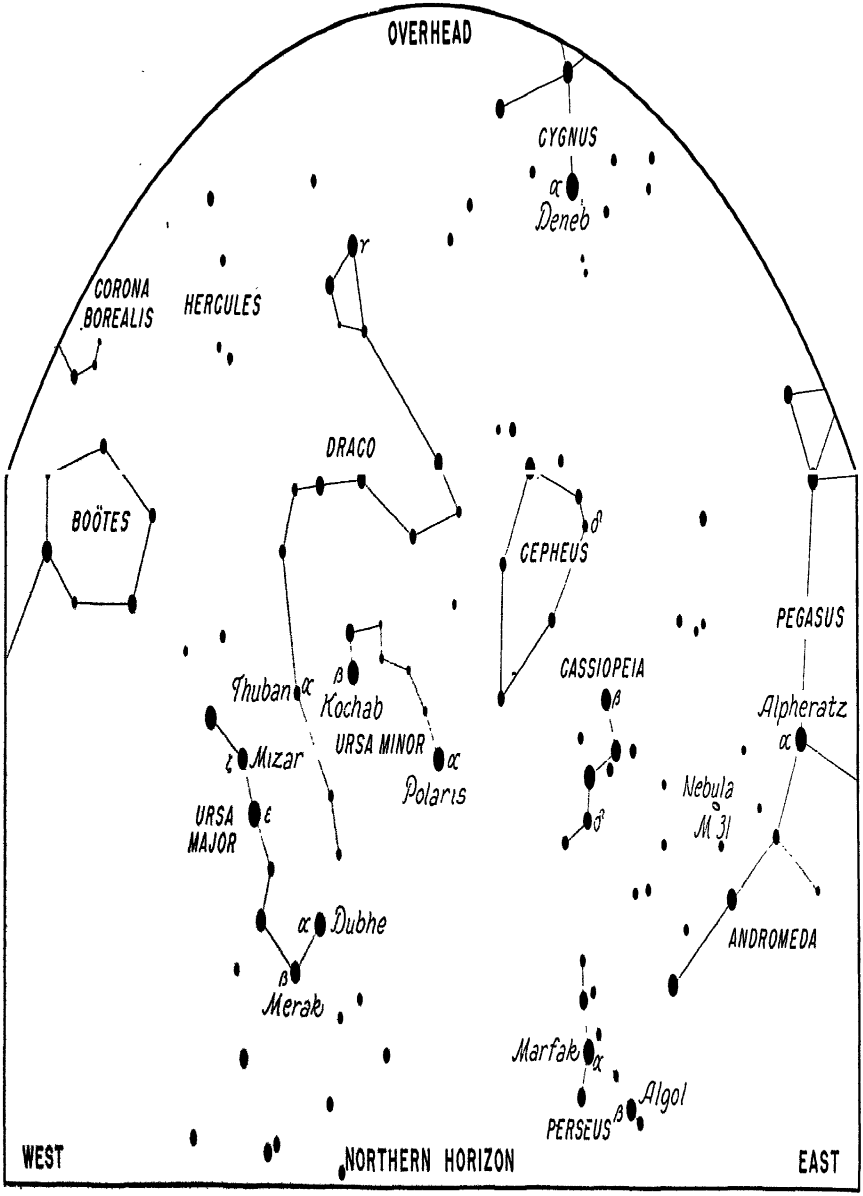
MAP 6. The Southern Sky, 8:20 p.m., May 1



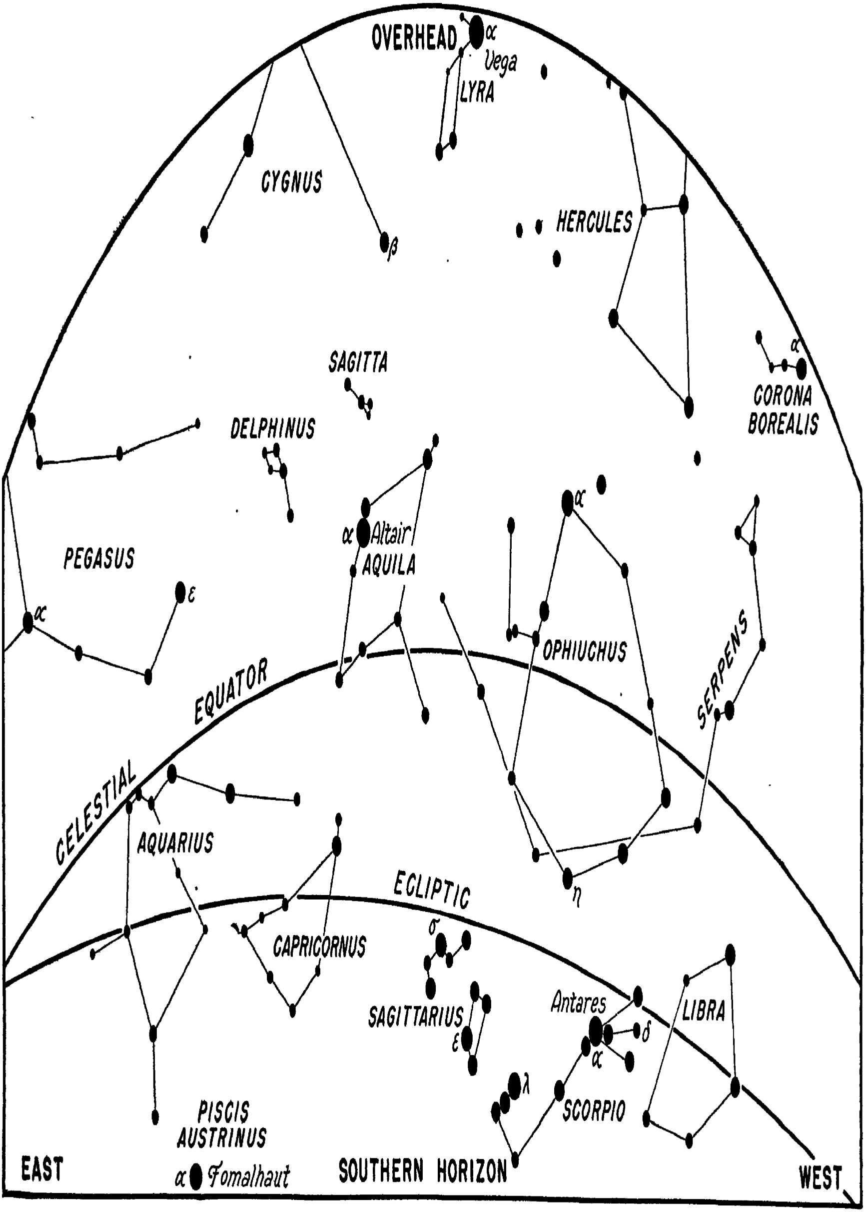
Map 7. The Northern Sky, 8:20 p.m., July 1



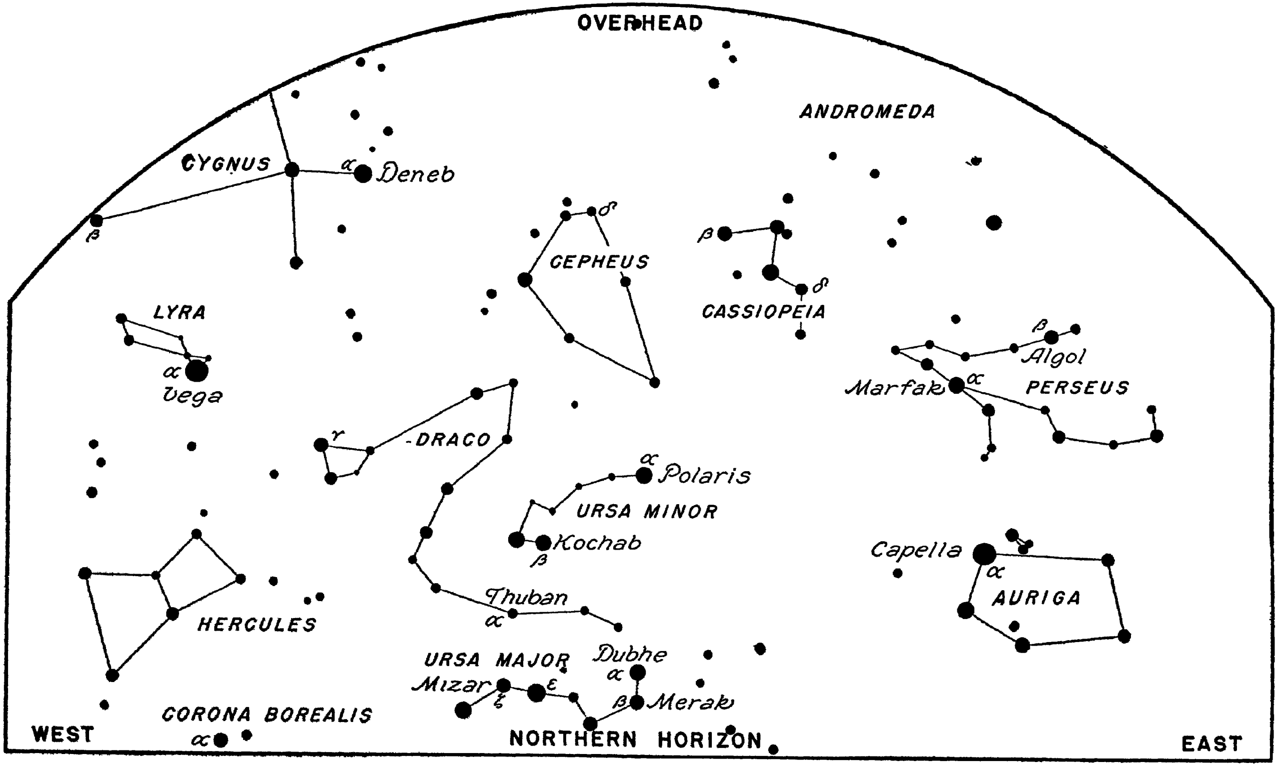
MAP 8. The Southern Sky, 8:20 p.m., July 1



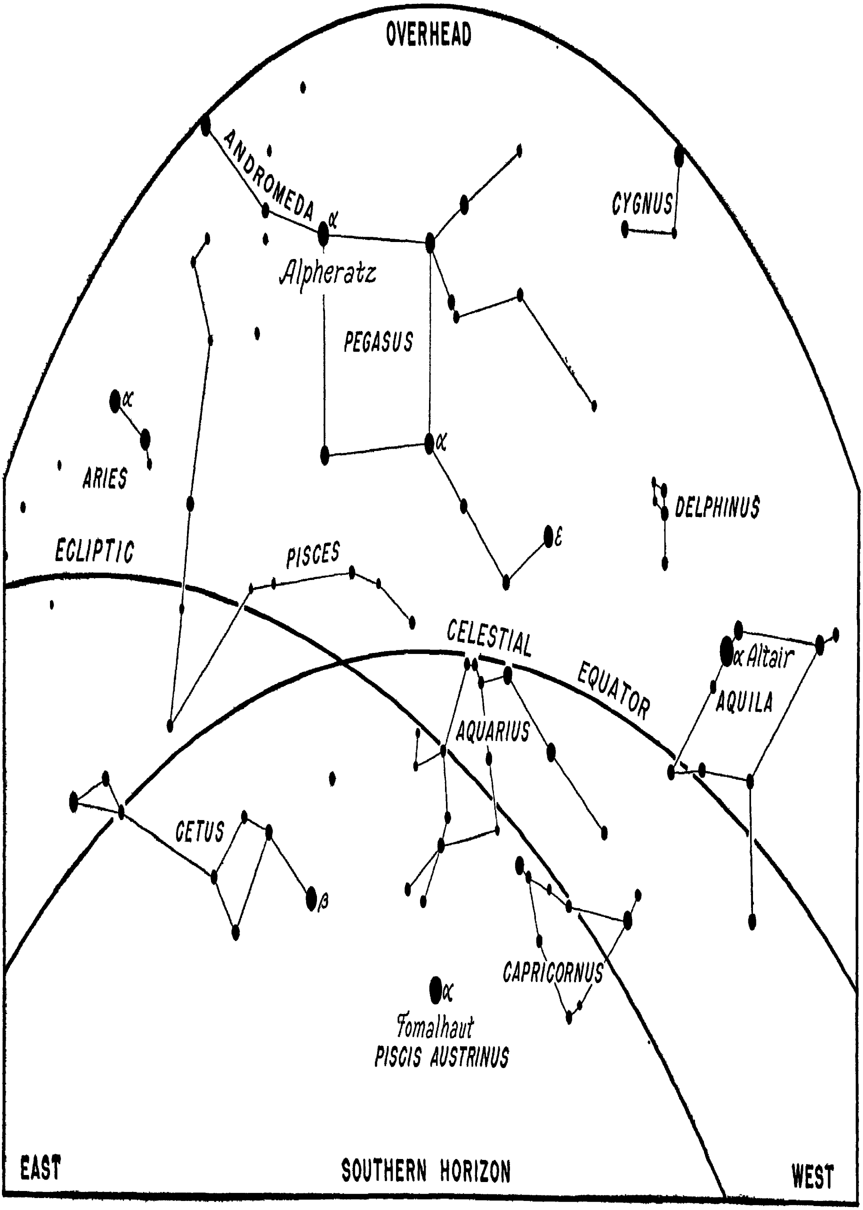
Map 9. The Northern Sky, 8:20 p.m., September 1



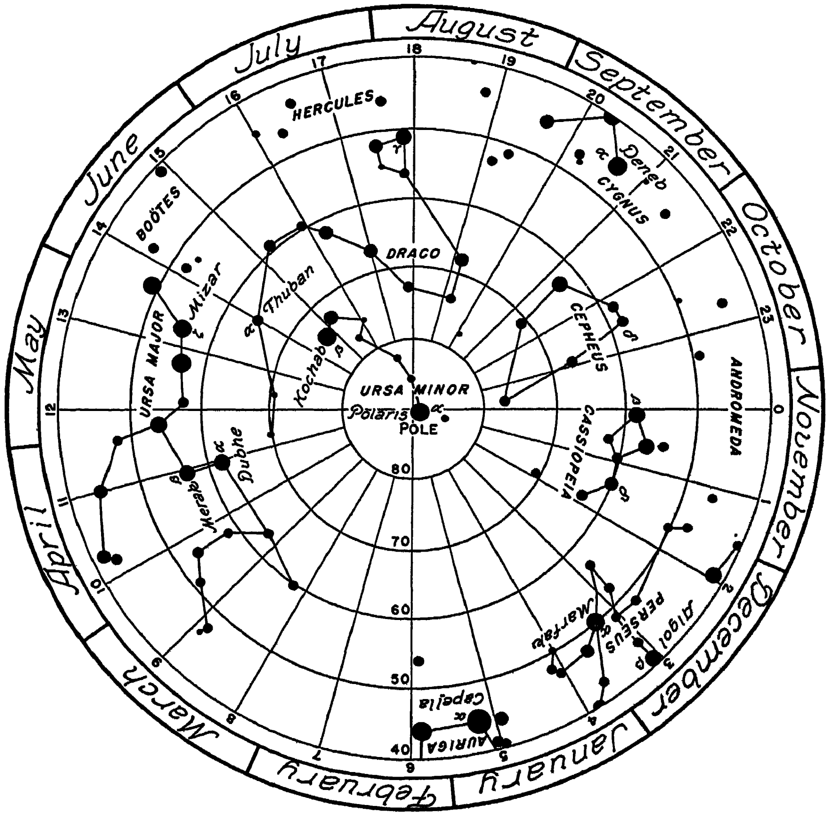
Map 10. The Southern Sky, 8:20 p.m., September 1



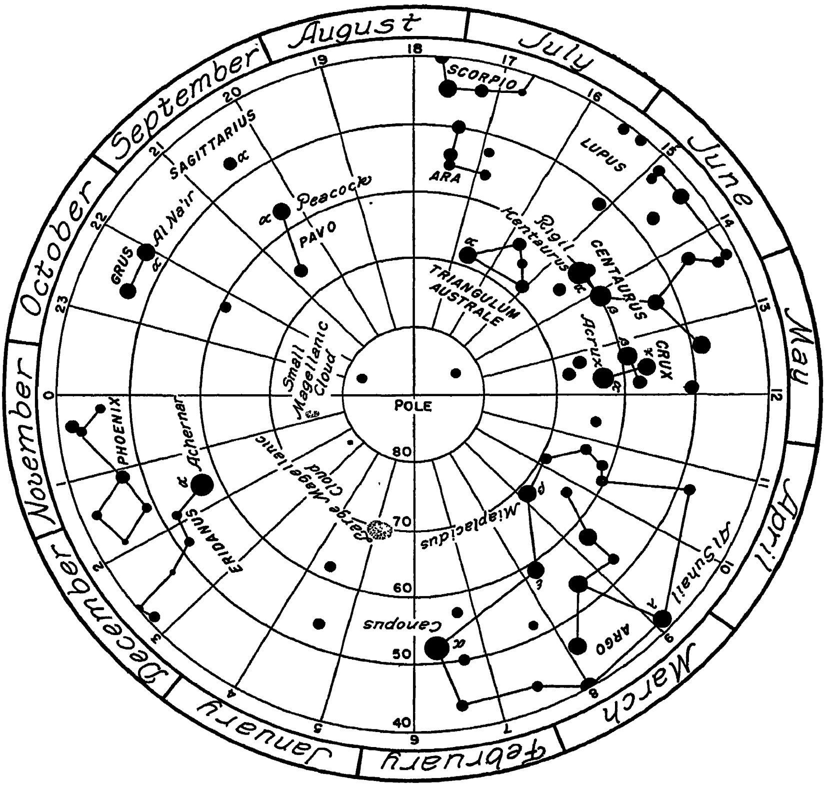
MAP 11. The Northern Sky, 8:20 p.m., November 1



Map 12. The Southern Sky, 8:20 p.m., November 1



MAP 13. The Northern Circumpolar Constellations



MAP 14. The Southern Circumpolar Constellations

☆ III ☆

Telescopes

Our knowledge of the stars has been obtained, first by a study of the light with various instruments, and second from accurate measurements of the position. The telescope, the chief instrument of the modern astronomer, collects hundreds of times as much light as the pupil of the eye. The magnifying power of a telescope makes possible the solution of many problems which could not be solved before the days of the telescope. By measuring small displacements we now are able to get the distance not only of the Sun and of the planets but of the nearest stars. Having the distance of the nearest stars by direct measurement, we get the distance of other stars by indirect measurement. The telescope enables man to study objects which are thousands of times too faint, and in apparent size hundreds of times too small, for viewing with the unaided eye.

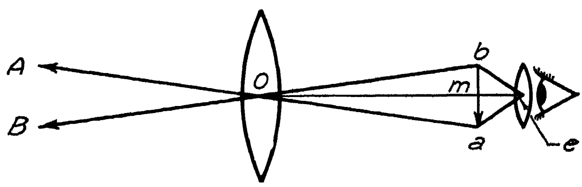


FIG. 15. The Optical System of a Simple Telescope

The first telescope was made by Lippershey, a Dutch spectacle maker, in 1608. He applied for a "patent" in October of that year, submitting a model with his application. The magnifying power probably was about three. In 1609 Galileo learned of this telescope and by 1610 had constructed a telescope with a magnifying power of thirty. This is considered the first astronomical telescope.

These first telescopes were similar to the modern opera glass, having a convex glass to form the image and a concave negative eyepiece. They gave an erect image but had a very small field of view.

Although primarily a mathematician, the astronomer Kepler suggested using a convex lens for the eyepiece in the telescope. This gave an inverted image, which was not objectionable in astronomy, and a larger field of view which was desirable. It was a definite improvement in telescopes, and has been used ever since.

The simple *refracting telescope* consists of a convex lens, O, called the object glass or objective, and a smaller convex lens, e, called the eyepiece. (See Fig. 15.)

Magnifying Power. In Fig. 15 we shall suppose that ray of light A is coming from one star and that ray of light B is coming from another star. Then the angular distance between them as seen with the naked eye would be AOB which also equals aOb. As seen through the telescope, the angle of separation is aeb, which is larger than AOB. From trigonometry, the following relation holds:

$$\tan 1/2\ aOb = mb/mO, \text{ and } \tan 1/2\ aeb = mb/me.$$

Since the angles are small, the arcs can be considered equal to the tangents, whence

$$1/2\ aOb = mb/mO, \text{ and } 1/2\ aeb = mb/me.$$

Angle aeb is the apparent distance as seen in the telescope, and aOb is the apparent distance as seen with the naked eye. The ratio is the magnifying power, or magnification, M. From the preceding equations

$$M = aeb/aOb = mO/me$$

where mO is the distance from the objective lens to its focus, commonly called the focal length of the objective lens, which may be denoted by F, and me is the focal length of the eyepieces, which may be denoted by f. Substituting in the preceding equation

$$M = mO/me = F/f,$$

or, the magnification of a telescope is the focal length of the objective divided by the focal length of the eyepiece. Any moderate

sized telescope is equipped with several eyepieces, giving several magnifying powers.

The Best Magnifying Powers. It has been found by experience that it is rarely worthwhile to use a magnification of more than 50

FIG. 16. The 82-inch Telescope of the McDonald Observatory, Mt. Locke, Texas. Photograph from Yerkes Observatory and the University of Chicago Press

per inch of aperture on a telescope. In fact, a lower power than 50 per inch is usually preferable. Higher powers give larger images, but they are of poor quality and less, rather than more, is seen.

To see faint objects, a magnification for which the beam of light issuing from the telescope practically fills the pupil of the eye is

preferable. The diameter of the pupil in darkness is seven to eight millimeters, or almost one-third of an inch. The diameter of the beam of light issuing from the eyepiece of a telescope can be found by dividing the aperture of the objective by the magnification. Hence, to obtain an issuing beam between one-third and one-fourth of an inch in diameter, or to fill the eye as well as possible, one should use a power of between three and four per inch of aperture.

A well-equipped telescope, therefore, should have a low power eyepiece of between three and four per inch of aperture, for studying faint objects, and other powers up to a highest of about fifty per inch of aperture for use where high magnification is desired. To illustrate, for a 10-inch telescope the lowest power should be between 30 and 40, and the highest power should be about 500.

Telescopes for small colleges often have been purchased by people who overestimate the importance and possibilities of magnification, and do not understand that for much astronomical work low powers are preferable because they show fainter objects and give a larger field. Consequently, an astronomer accepting a college position may find his telescope equipped with several eyepieces of such high power that they are rarely or never used, even on close double stars, and no eyepieces of as low power as he should use for showing nebulae and star clusters.

Focal Ratio. If one considers a telescope, or a camera, with an objective of a given focal length, the image is of a certain size. By doubling the diameter of the objective, the amount of light falling on the image is increased by four. If the diameter of the objective is kept the same, but the focal length doubled, the diameter of the image is doubled, and the amount of light per unit area of the image is decreased by four. Increasing the aperture of the lens, or decreasing its focal length, increases the brightness of the image, and hence the "speed" of the camera or telescope.

The *focal ratio* of a camera or of a telescope is obtained by dividing the diameter of the lens into the distance from the objective lens to the image. The distance from the objective lens to the image is very nearly the length of the telescope, or the length of the camera, when it is focused. Hence, the focal ratio of a telescope can be obtained approximately by dividing the aperture of the objective lens (or mirror) into the length of the telescope.

The focal ratio of a camera, or a photographic telescope, is a

measure of its speed, as you have read. The shorter focal ratios have greater light gathering power, and a camera with short focal ratio will obtain a picture with a shorter exposure time. A telescope

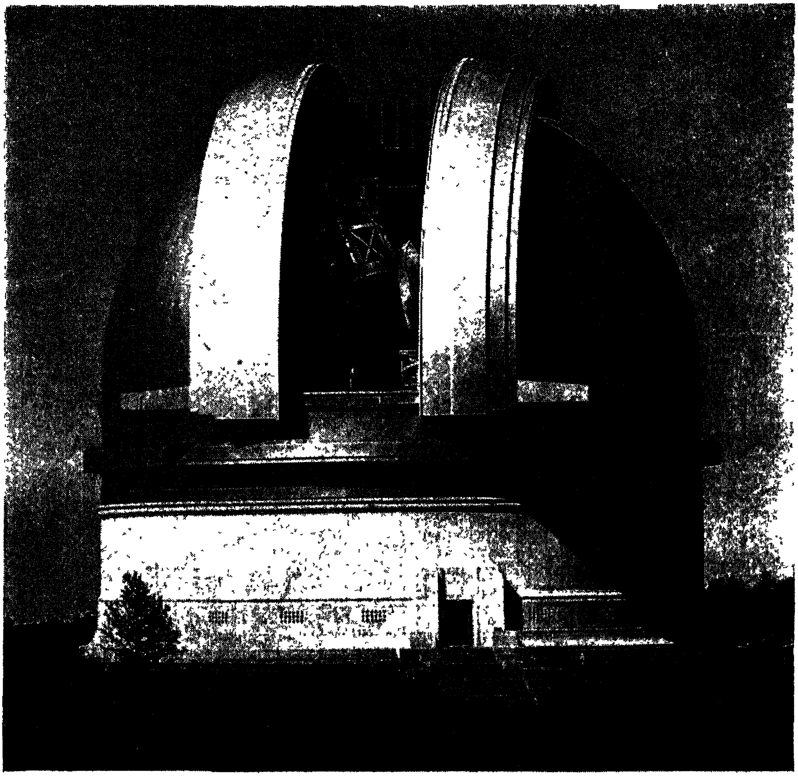


Fig. 17. The Dome for the 200-inch Telescope at Palomar Mountain. The height, about that of a 12-story building, is indicated by the man shown standing in the open slit. Photograph from California Institute of Technology

with a short focal ratio will show, or photograph, fainter nebulae and star clusters.

The focal ratio of the early telescopes went as high as 300. In 1890 the big telescopes were being built with focal ratios of about $f/20$. In 1900 cameras had focal ratios of about $f/11$.

In more modern times lenses and mirrors have been improved

so that cameras and telescopes of shorter focal ratios can be built. The 60-inch and 100-inch telescopes at Mount Wilson have focal

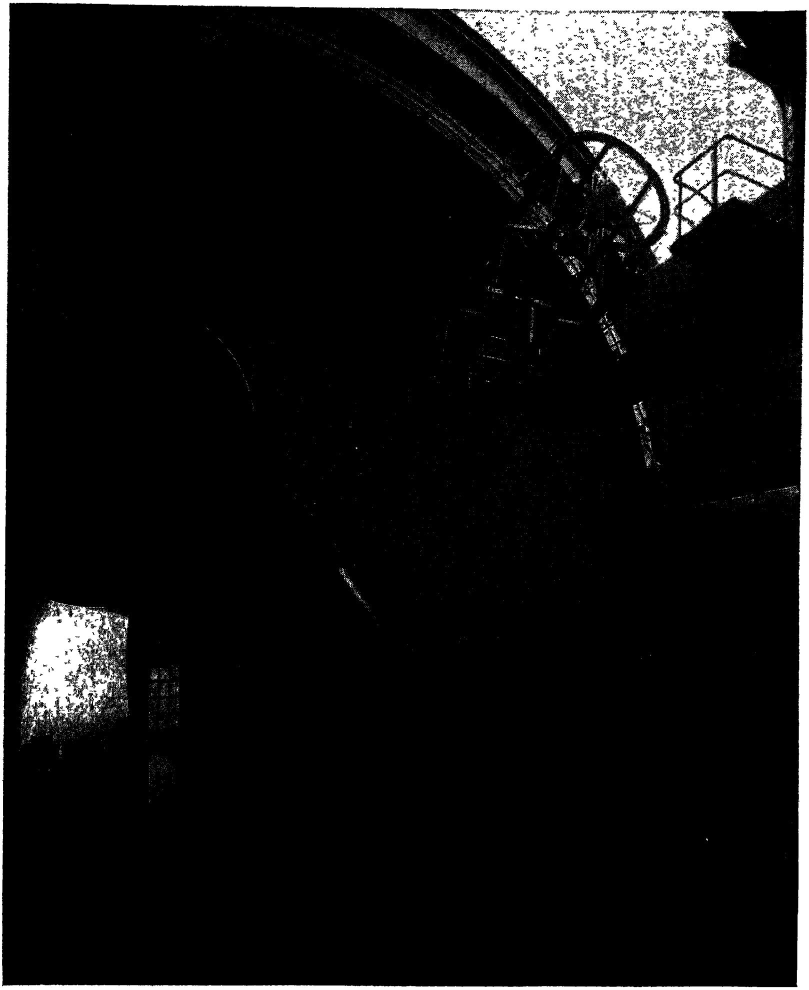


FIG. 18. The 72-inch Telescope of the Dominion Astrophysical Observatory, Victoria, British Columbia. Photograph from Dominion Astrophysical Observatory

ratios of about $f/5$. The 200-inch telescope at Mount Palomar will have a focal ratio of $f/3.3$. Moving picture cameras have focal ratios

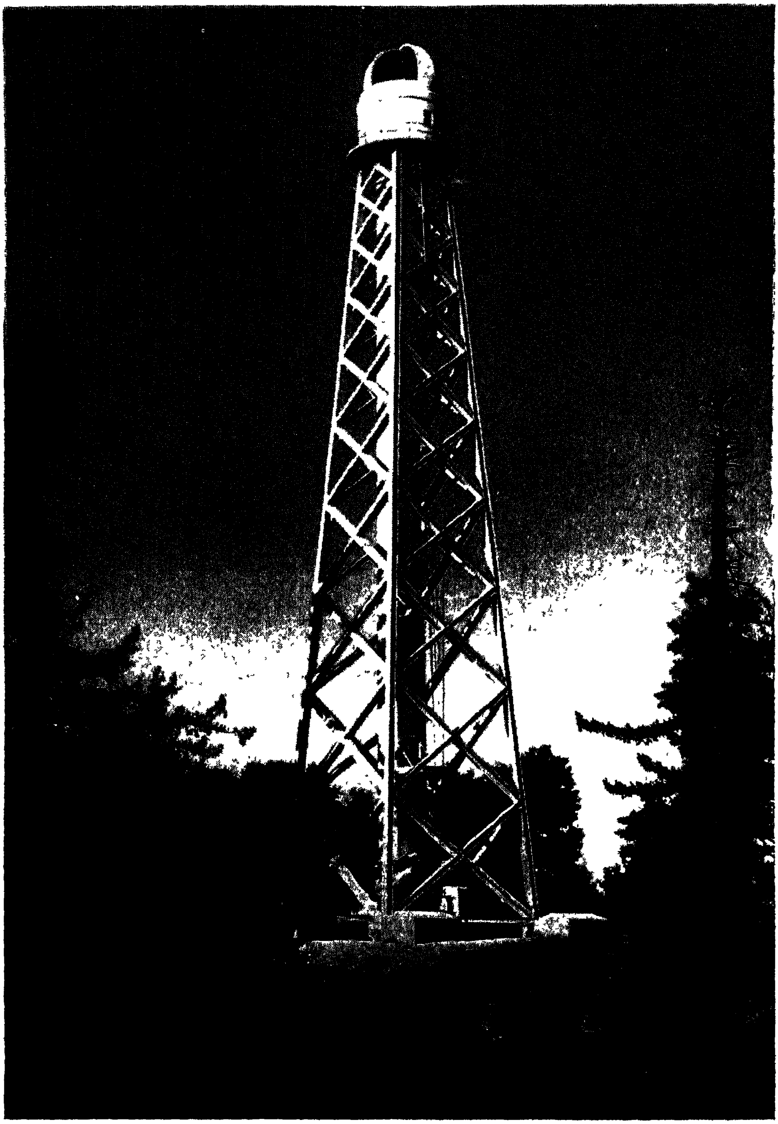


FIG. 19. The 150-foot Tower Telescope at Mount Wilson. Photograph from Mount Wilson Observatory

from $f/1$ to $f/3$. The new Schmidt astronomical cameras are being built with focal ratios from $f/0.67$ to $f/2.5$. A Schmidt telescopic camera has been designed, but not yet constructed, with a focal ratio of $f/0.38$.

The telescopes of short focal ratios will show or photograph fainter nebulae, star clusters, comets, or meteors. Where there is plenty of light, as with the Sun or double stars, a long telescope will give greater magnification.

The Two Functions of a Telescope. The two functions of a telescope are light gathering (showing faint objects) and magnification. For the greatest light gathering power, one should have a telescope of relatively short focus and low magnifying power. For the greatest magnification, one should have a relatively long telescope, to make a large image.

The difference is illustrated by the reflecting telescopes of focal ratio f/5, or less, for study of faint objects, and the tower telescopes of focal ratio f/150 for work on the Sun.

Defects of Simple Lenses. A single lens with spherical surfaces has certain defects which make the image somewhat imperfect. The three chief defects are the following:

1. *Spherical aberration.* Rays passing through the outer portion

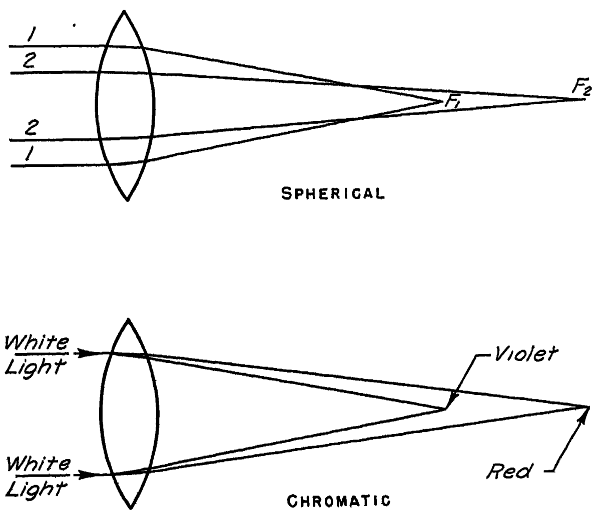


FIG. 20. Spherical and Chromatic Aberration

of the lens are brought to a focus more quickly, or bent more sharply, than those passing near the middle, as Fig. 20 shows.

2. *Chromatic (or color) aberration.* The blue rays are bent more sharply than the red, and so brought to a focus nearer the lens, as Fig. 20 shows.

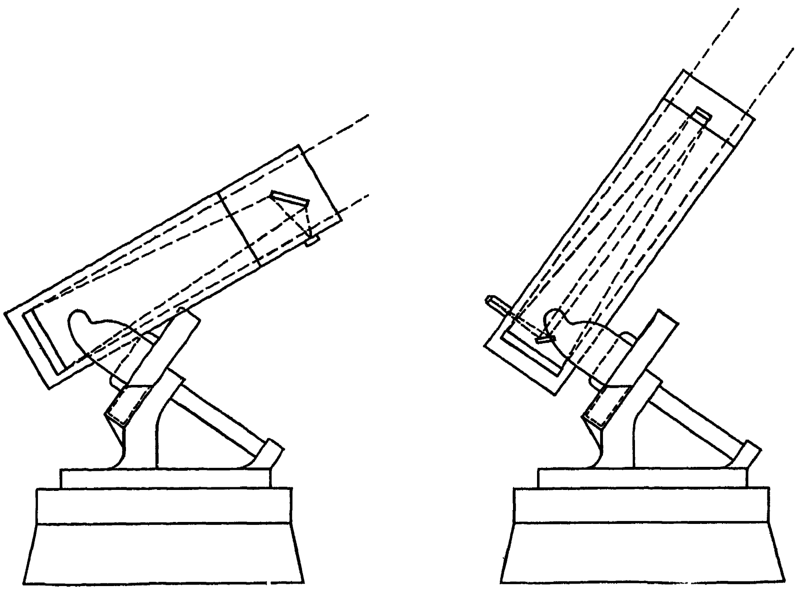


FIG. 21. Optical Systems for a Reflecting Telescope. The Newtonian plan is on the left, the Cassegrainian on the right

3. *Curved field.* Stars at the edge of the field do not come to a focus in the same plane as stars in the middle. In photographic work especially, it is desirable that a relatively wide field be focused in the same plane.

Overcoming Defects of Lenses. The defects are less with a very long focus as the rays are not bent so sharply, so some very long telescopes were made in the 1600's. Telescopes from 20 to 25 feet long were very common. One 150 feet long with a 6-inch lens was used.

Sir Isaac Newton (1643-1727) pointed out that using a concave (parabolic) mirror, instead of an objective lens for forming the

image, eliminates both chromatic and spherical aberration. He made a model in 1672 of the first *reflecting telescope.*

Newton's telescope is excellent for light gathering, showing faint objects, but not so good for magnifying. Sieur Guillaume Cassegrain, a Frenchman, in the same year, 1672, published drawings of a plan for getting better magnification.

Neither the Newtonian nor the Cassegrainian form gives a wide field, but all the larger reflecting telescopes of modern times can be used in either form. Fig. 21 shows the path of light in the Newtonian and Cassegrainian systems.

A third method of eliminating the defects of the simple lens, is the compound lens, combining two or more lenses of different kinds of glass. This compound lens, which eliminates chromatic aberration, is called the *achromatic lens.*

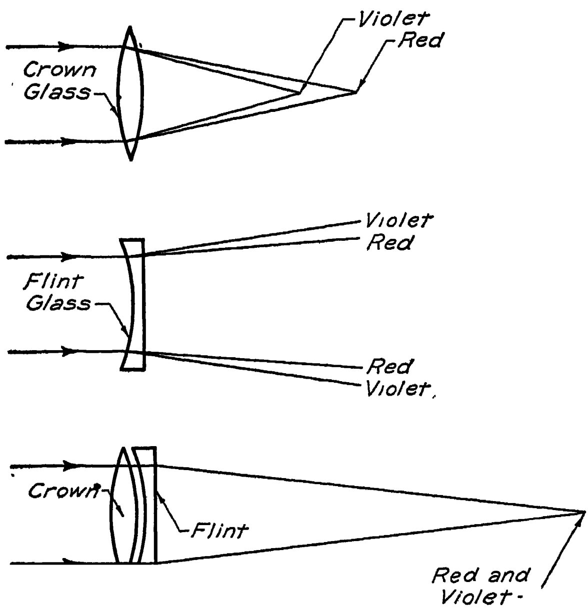


FIG. 22. The Achromatic Lens

The simple achromatic objective has two components, a convex lens of crown glass, usually in front, and just behind it a concave lens of flint glass. The flint glass having a relatively higher disper-

sion than crown glass brings together the rays of light so that with a two-lens combination, any two desired colors can be brought to a focus at the same point. (See Fig. 22.) The focal length of the compound lens is double that of the single lens of crown glass. By careful computation of the curves for the surfaces of these lenses, it is possible to correct not only for the chromatic aberration but also to correct for the spherical aberration. It is also possible to compute the curves to give a flat field over a much wider angle than for a simple lens.

Many photographic telescopes have three, or even four, components in the objective. Some cameras have even more. With sev-

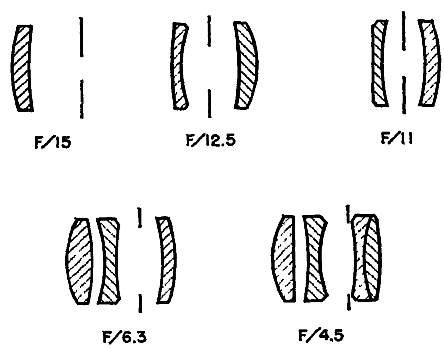


FIG. 23. Typical Camera Lens Systems

eral components, both visual and photographic light can be brought to a good focus over a wide field. This latter point is important in cameras and in photographic telescopes. Fig. 23 shows camera lenses of various focal ratios. Remember that smaller focal ratios have shorter focus and are faster. The objectives must be relatively very thick if a fast lens corrected over a wide field is desired.

Resolving Power. Longer focus telescopes give larger images and are better where magnification is desired, as on the Moon, the planets, and double stars; but there is a limit to the amount of magnification for a lens of given aperture. This would be expected by anyone who has used cameras of various sizes. Photographs taken with a miniature camera can be enlarged, but not to the same size that a photograph made with a 5 by 7-inch camera, of the same quality, can be enlarged.

It has been found by experience, and it can be verified by calculation from the laws of optics, that two stars can be barely separated in a telescope of aperture *a* if the distance apart of these stars d is given by the formula d = 4.″5 divided by *a*. With a telescope of 5-inch aperture stars whose distance apart is 0.″9 can be barely separated on the best nights if the instrument is of the best

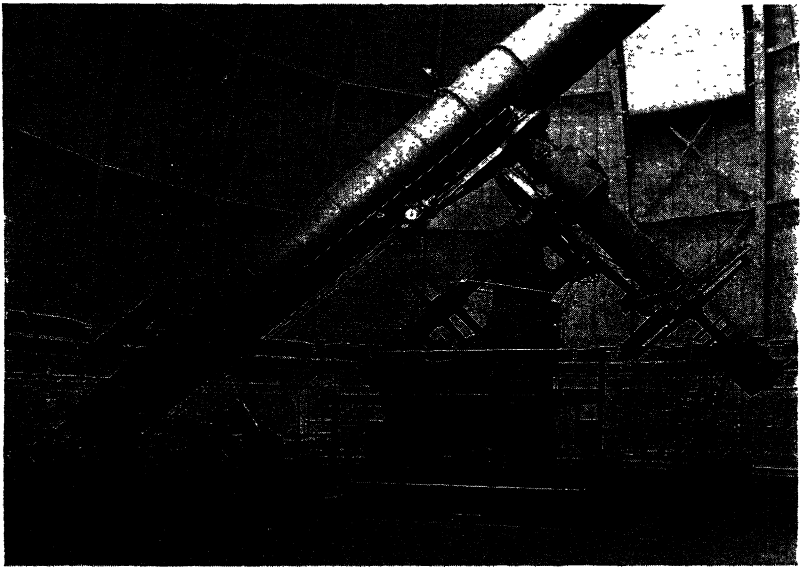


FIG. 24. The 40-inch Yerkes Telescope. The rising floor is at the highest position. Photograph from Yerkes Observatory and University of Chicago Press

quality. With the 40-inch telescope at Yerkes Observatory stars whose distance apart is 0.″11 can be separated on the best nights. No amount of magnification can lower this limit. This refers to stars of just about the same brightness, which can be separated in spite of some overlapping of the images. If one star is much fainter than the other, as in the case of Sirius and its companion, the distance apart must be much greater if the fainter star is to be seen.

Difficulties of Large Lenses. The 40-inch Yerkes telescope has the largest successful lens. A 48-inch telescope made in Paris about 1900 was a failure. The following are some reasons why larger lenses have been failures:

1. A lens can be supported only at the edge. When it is large, it tends to sag in the center, changing the shape of the lens and distorting the image. The 40-inch Yerkes lens sags appreciably enough to distort fine photographic work but not visual work.

2. A big achromatic lens means an enormous thickness of glass, which absorbs much light. This is especially true for wide-field short-focus lenses, which have four or even more components. The largest refracting telescopes have only two component objectives, and hence are not short-focus.

3. A heavy lens at the end of a long telescope tube causes the tube to sag, moving the object glass out of line.

Large Reflectors. About 1900, it became evident that refractors could not be made larger than 40 inches, and that that size could be reached only with long-focus instruments. Astronomers, therefore, turned to the metal-on-glass reflecting type for the larger instruments. Several telescopes of 72-inch aperture or more are now in service, the largest being the 100-inch Mount Wilson telescope.

The 100-inch Reflector. In October, 1906, Dr. George E. Hale, then the Director of Mount Wilson Observatory near Pasadena, California, announced plans for a 100-inch reflecting telescope. A 60-inch reflecting telescope at Mount Wilson was then the largest in the world. Difficulties were encountered in casting the big glass disk for the mirror, and other unforeseen difficulties delayed completion of the instrument.

In 1917, during World War I, it was announced that the big telescope would be completed soon. In August, 1919, after the close of the war, tests of the performance were started. It was found that the instrument was a complete success, the gain in power over the 60-inch being equal to the theoretical gain from the difference in aperture. This was thirteen years after the instrument was announced.

The 200-inch Reflector. In 1926, F. G. Pease of the Mount Wilson Observatory published articles on "The Design of a Very Large Telescope." In these articles he published preliminary drawings, and a discussion of the problems involved, for a 300-inch reflecting telescope.

In 1928, Dr. Hale, of the Mount Wilson Observatory, announced that funds had been secured for the construction of a *200-inch* reflecting telescope. Notice that although the preliminary plans were

for a 300-inch reflector, funds were secured only for a 200-inch. This, however, was double the aperture of the largest telescope then in existence.

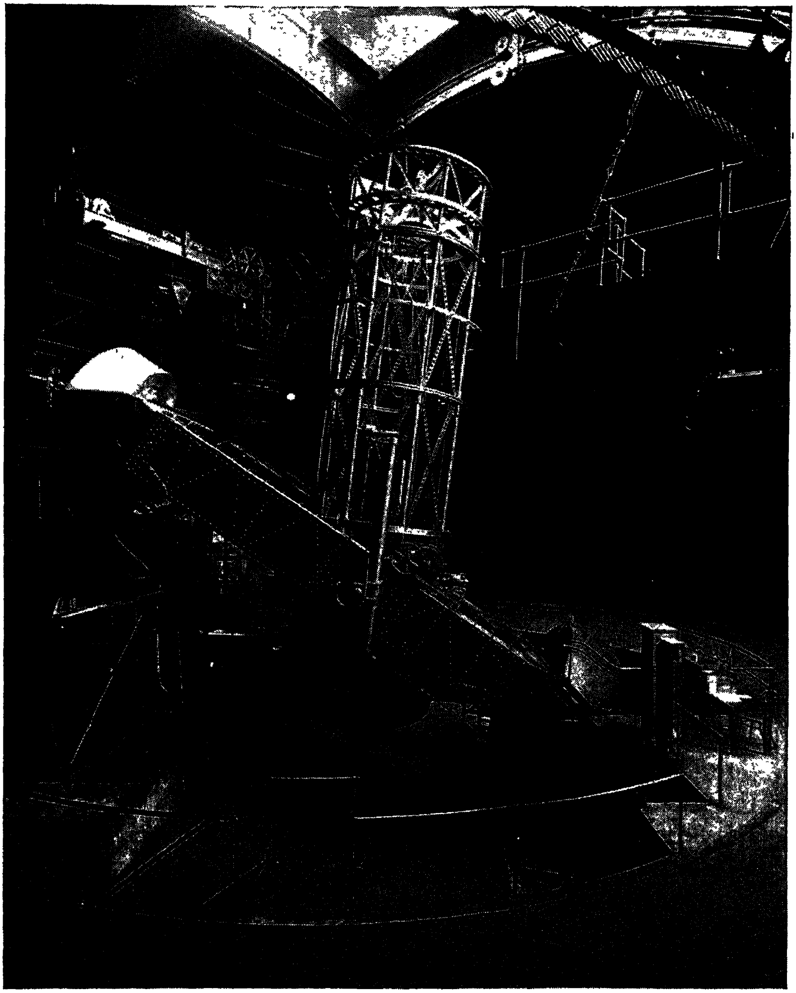


FIG. 25. The 100-inch Telescope at Mount Wilson. Photograph from Mount Wilson Observatory

In June, 1941, it was announced that the mounting was nearly completed and that the difficulties in supporting the large mirror

had been overcome. With these problems solved, the completion of the great instrument was "in sight."

The 100-inch telescope was completed thirteen years after plans for its construction were announced. Presumably the 200-inch would have been completed in fourteen years or thereabouts, if World War II had not stopped work on the great instrument.

Advantages and Disadvantages of Reflectors. Reflectors can be built larger than refractors, since the difficulty of a sagging object glass is avoided. The mirror can be supported across the back. The difficulties of thickness of glass, and of imperfections in the glass, major problems with large lenses, are avoided, because the light does not enter the glass of the mirror at all. The reflecting metal surface is on the front of the mirror. The sagging of the tube is avoided, because the heavy mirror is at the lower end of the tube, where the tube can be supported, instead of at the upper end, as with the lens.

The reflector can be built large, therefore, and in the Newtonian form can have great light-gathering power. In the Cassegrainian form it can have great magnifying power. (See Fig. 21.) A disadvantage is that the reflector has a very small field as compared to the refractor.

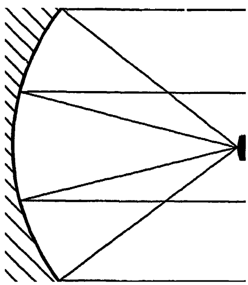
Combination Reflecting and Refracting Telescopes. The *Schmidt* photographic telescope, or camera, is a modern instrument which uses a mirror at the lower end of the tube, and a single thin lens at the upper end. Fig. 26 shows the path of the light rays for two types of Schmidt cameras. Camera I shows the optical plan of practically all Schmidts in use today, 1942. Camera II is a new design faster than any instrument yet made. Because of the war no camera of this type has been completed except in design.

The Schmidt telescope has the speed of a modern reflector, and the wide field of a modern refractor. Since it has only a single thin lens, it can be built much larger than a wide-field refractor. The mirror can be supported as in a reflecting telescope, and the lens has such a small curvature that the sag can be considerable without causing any distortion.

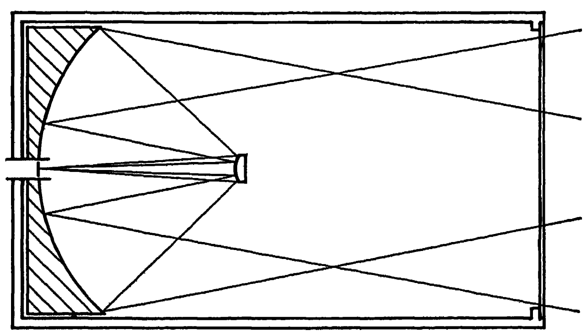
The Schmidt telescope photographs exceedingly faint objects for its size, it can be made exceedingly fast, and it has a wide field of view, so that the area of sky photographed is several hundred times that covered by a reflecting telescope of the old type. The Schmidt

has been termed the greatest advance in telescope design in 200 years.

Equatorial Telescope Mountings. Except for such problems as observations for time, latitude, or longitude, the telescope is mounted



SCHMIDT CAMERA I



SCHMIDT CAMERA II.

FIG. 26. Two Types of Schmidt Cameras

in *equatorial* fashion. That is, the main axis is parallel to the axis of the Earth, so that a uniform rotation on this axis will counteract the rotation of the Earth. At the North Pole such an axis would be vertical, and at the equator such an axis would be horizontal.

The uniform rotation, to counteract the rotation of the Earth, is produced by what the astronomers call the *driving clock* of the

telescope. The ordinary clock, controlled by a pendulum or a balance, cannot be used since it would move the telescope with a jerking motion. Some of the older telescopes were driven by clepsydras, or water clocks. As the flow of water can be made quite uniform, these clocks were reasonably satisfactory.

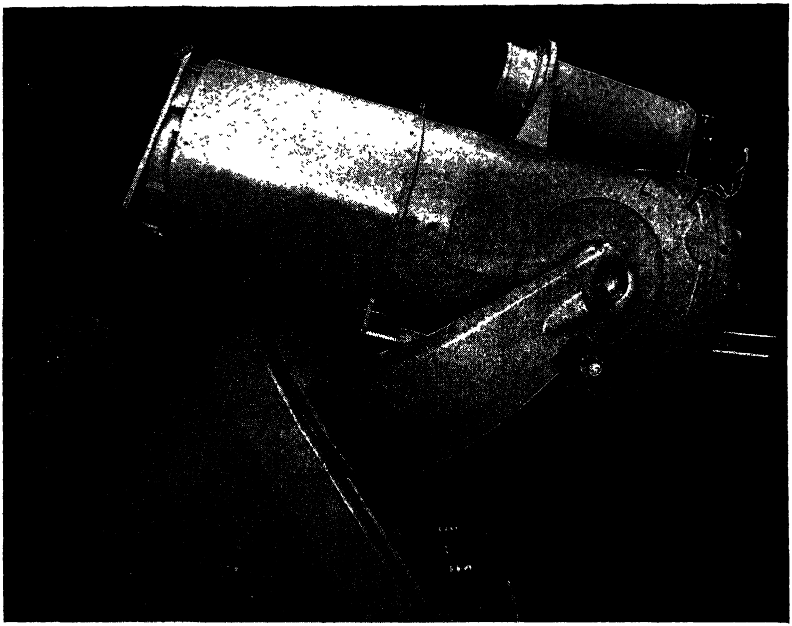


FIG. 27. The 18-inch Schmidt Telescope at Palomar Mountain. Photograph from California Institute of Technology

Most of the telescopes made from 1870 to 1930 had clockwork controlled by balls thrown outward by the centrifugal force of rotation until they came in contact with some braking device. These whirling balls made the motion of the telescope reasonably uniform. Most telescopes made since 1930, however, are driven by *synchronous motors*, similar to the motor which operates the modern electric clock. These motors produce a more uniform motion than the clockwork of the older telescopes.

The chief types of equatorial mountings are as follows:

1. The *standard* type. The Lick telescope, the Yerkes telescope,

and most refractors, are mounted in this way. The mounting is on a single pier, and there is a counterweight to balance the telescope, which can be pointed readily at any star in the heavens. (See Fig. 28.)

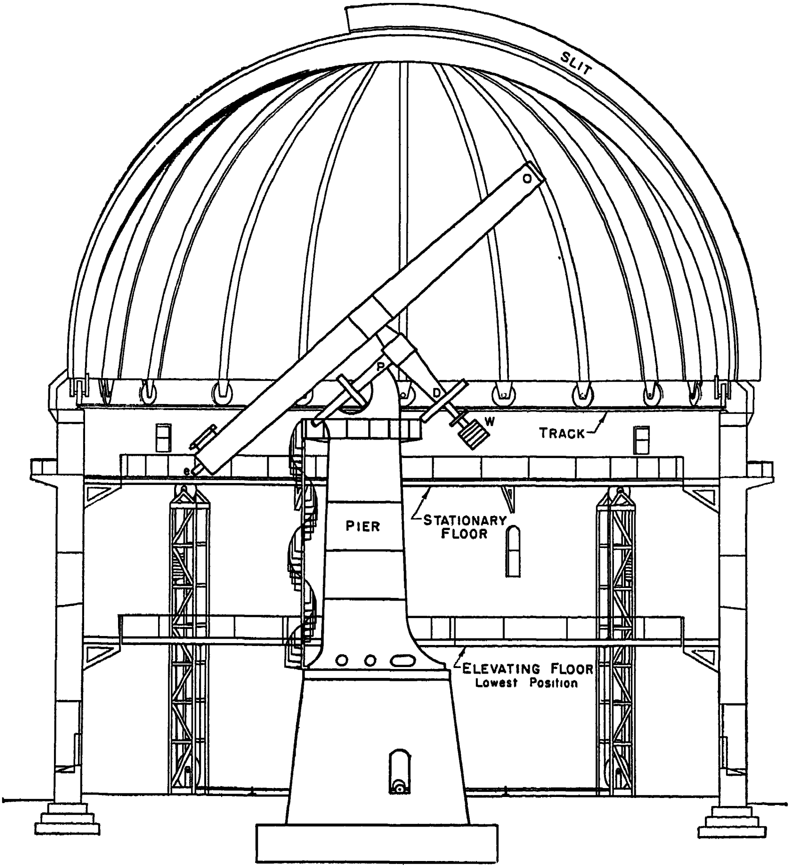


FIG. 28. The Yerkes 40-inch Telescope and Its Dome

2. The *two-pier* English style. The 72-inch reflecting telescope at Victoria is mounted in this way. The axis is much longer and heavier and is supported by two piers instead of one. The counter-weight is retained so that the axis carries almost double the weight

of the telescope. With this mounting the telescope can be pointed readily at any star in the heavens. (See Fig. 29.)

3. The *yoke*, or *split-axis*, mountings. Here the axis is large and heavy, supported by two piers as in the previous mounting, but it is split, with the telescope swinging between the two halves. This eliminates the counterweight, but one cannot point the telescope at

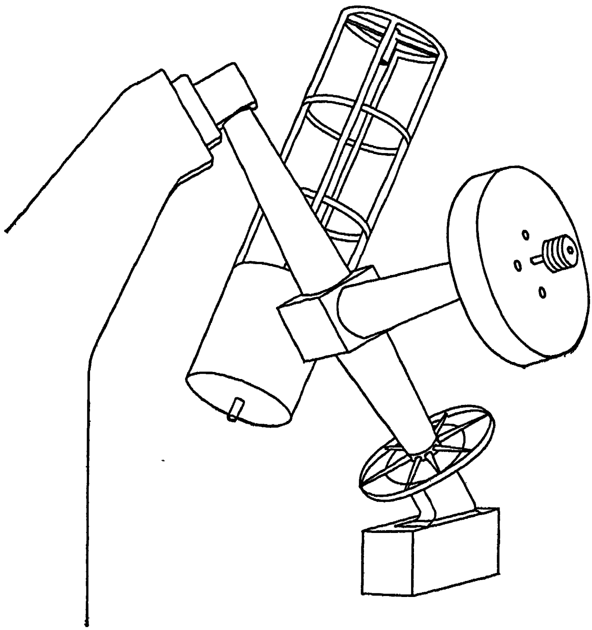


FIG. 29. The Two-pier English Mounting

the North Star as it bumps against the upper end of the axis. This mounting is used for the 100-inch at Mount Wilson. (See Fig. 30.)

4. The *fork* mounting. This style is used for the 60-inch reflector of the Mount Wilson Observatory. The telescope swings in a big fork at the upper end of the axis. This style eliminates the counterweight and permits pointing anywhere in the heavens. The weight of the heavy telescope at one end of the axis, however, makes considerable strain on the supports. (See Fig. 31.)

5. The *bowl* mounting. This has been developed for portable telescopes. The polar axis is a bowl, which rides in rollers, and the

telescope and bowl can be lifted out when one desires to move the instrument. The counterweight is eliminated, the telescope can be pointed anywhere in the heavens, and a motor drive counteracts the rotation of the Earth, so that once set, the telescope will follow a star. (See Fig. 31.)

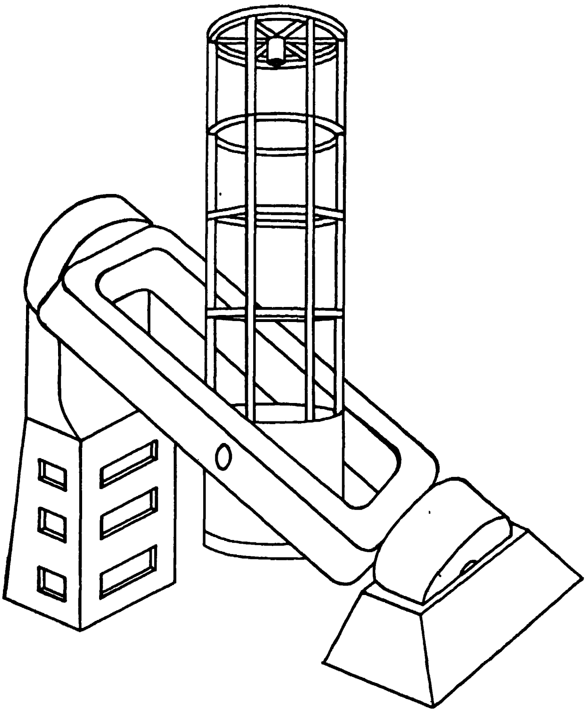


FIG. 30. The Yoke Mounting

6. The *horseshoe* type. The 200-inch mounting is a combination of the fork and yoke mounting. The upper end of the fork is joined by a horseshoe-shaped support which rides on rollers. It furnishes a support above the heavy telescope, yet permits pointing at any star in the heavens, including the North Star. (See Fig. 32.)

Solar Coelostat Telescopes. You have read in the earlier paragraphs on the functions of a telescope that the long focus instruments are the best for magnification, but are not so good for light gathering. In work on the Sun there is plenty of light, in fact too

much, so telescopes with a focal length of as much as 150 feet are used. Astronomers mount such instruments for work on the Sun either horizontally or vertically and in a fixed position. A mirror driven by clockwork reflects the light of the Sun at any time into this long telescope. Such a mirror, driven by clockwork to follow the heavenly bodies, is called a *coelostat.*

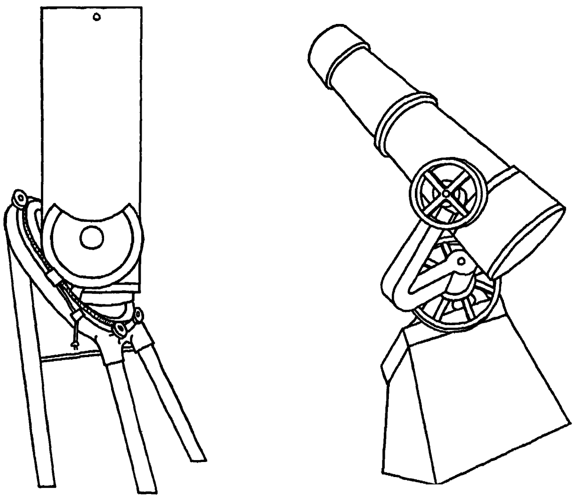


FIG. 31. The Bowl and Fork Mountings. A portable bowl mounting is on the left, a fork mounting at the right

Coelostat Sidereal Telescopes. Fixed telescopes fed by coelostat mirrors have been found very convenient for showing the heavenly bodies to students and visitors. With a coelostat telescope there is some loss of light and loss of quality of image because of the mirror, but the fact that the observer can remain in a heated room and in a fixed position is a convenience. Sidereal coelostat telescopes are mounted horizontally, like solar telescopes, or parallel to the axis of the Earth. Fig. 34 shows the coelostat mirror of the telescope of the Buhl Planetarium, in Pittsburgh, Pennsylvania.

The Transit Circle. The telescopes previously described are used for the study of faint objects, or for relatively accurate positions almost anywhere in the heavens. There are types of astronomical work, however, for which neither light-gathering power nor mag-

nification are the most important points. These are the determination of the right ascension and declination of the stars, and the determination of time, longitude, latitude, and direction.

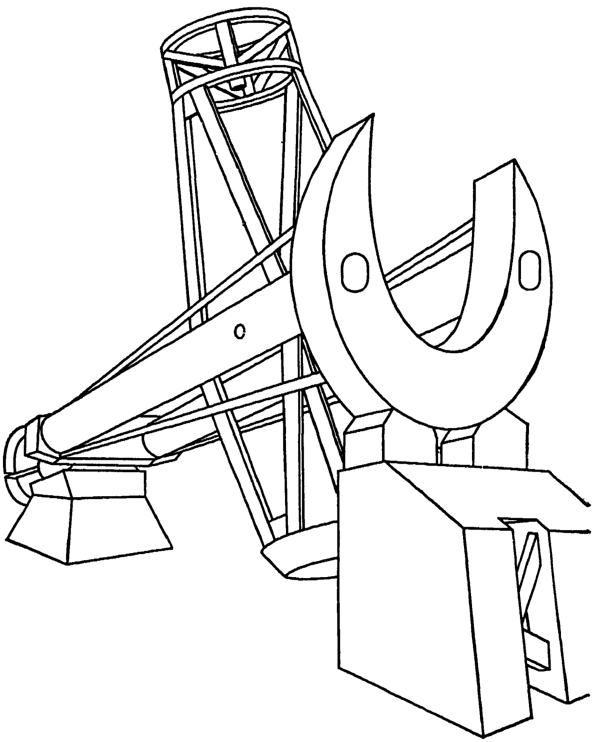


FIG. 32. The Horseshoe Mounting

For fundamental star positions astronomers use the *transit circle.* This is a substantially mounted telescope, usually with a lens of five- to nine-inch aperture. It has only one axis, which is in a horizontal east and west position. As the telescope swings, it can point only at objects on the meridian. The altitude, or zenith distance, of objects crossing the meridian can be read with accuracy and, with proper equipment, the time at which the object crossed the meridian can be recorded with accuracy.

For the most accurate determination of time, even the horizontal

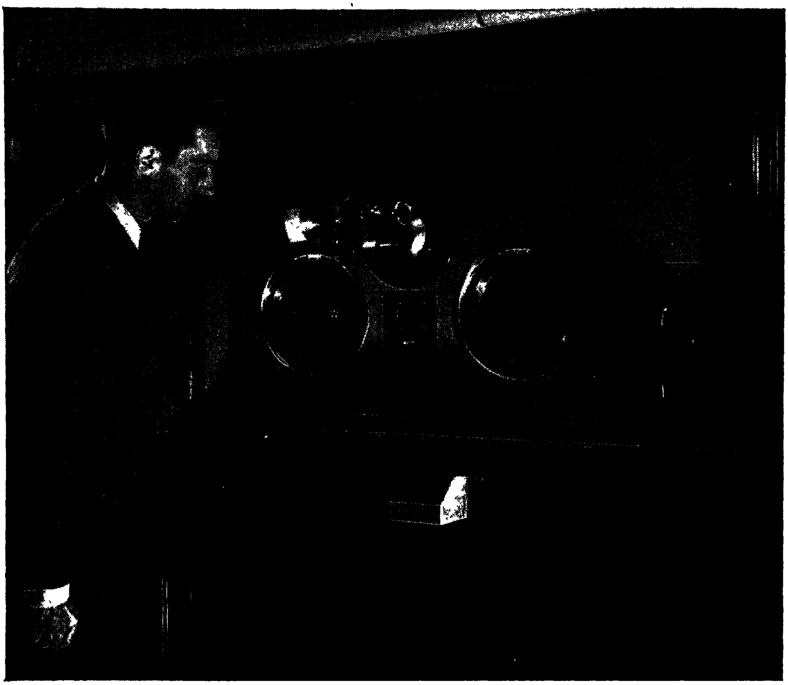


FIG. 33. The Eye End of the Buhl Planetarium Telescope. Photograph from Buhl Planetarium

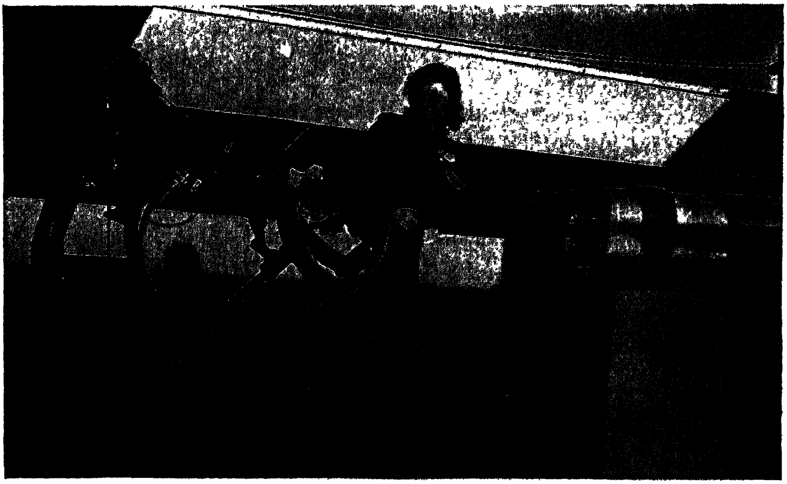


FIG. 34. The Objective Lens and Coelostat Mirror of the Buhl Planetarium Telescope. Photograph from Buhl Planetarium

axis is eliminated, and the telescope is fixed in a vertical position. It has no motion whatever, but a photographic plate can be driven by a synchronous motor to follow stars as they pass across the field of the telescope, which, of course, is centered on the zenith. This instrument is called the *photographic zenith tube.*

Surveyors, explorers, and navigators need portable equipment for the determination of azimuth (or direction), time, longitude, and

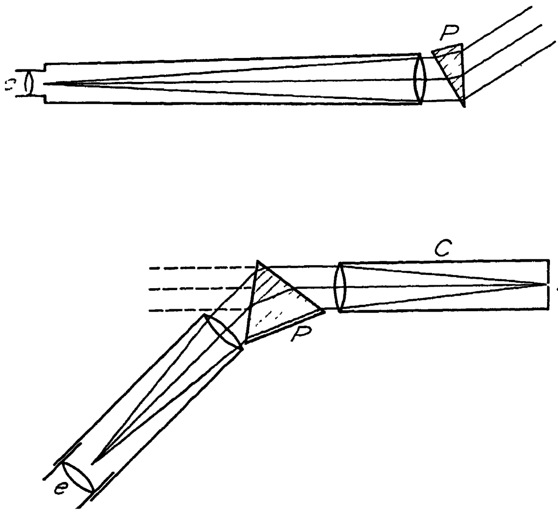


FIG. 35. Objective and Slit Prism Spectroscopes

latitude. Surveyors and engineers use chiefly the *theodolite,* or *engineer's transit,* a portable instrument with a telescope, of about one and one-fourth inches in aperture, mounted with a horizontal and a vertical axis. Explorers occasionally use the theodolite but often carry the sextant.

Sextant. This is a light instrument, with a telescope perhaps half an inch in diameter, with which altitudes or the angular distance between any two objects can be measured, while the instrument is held in the hand. The principal use of this instrument is in measuring the altitude of the Sun (or of a star). If the navigator brings the reflected image of the Sun down until the lower edge seems to just touch the visible horizon viewed directly, the reading will be

the altitude of the Sun after correcting for dip, refraction, semidiameter, and index error. A modern marine sextant is shown in the illustration on page 251, and an airplane bubble sextant is shown on page 256.

Instruments to Attach to the Equatorial Telescope. The *micrometer* is an instrument for measuring the distance and direction of

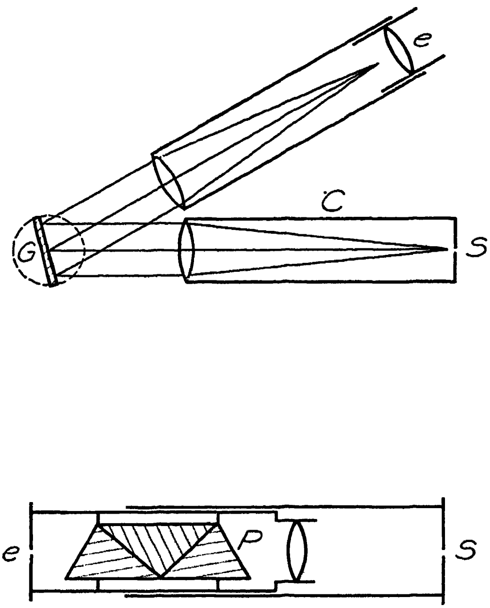


FIG. 36. Grating and Direct Vision Spectroscopes

one heavenly body from another. It may be used to get the position of a new comet from that of a known star; or it may be used to get the distance and direction of one component of a double star from the other. The *spectroscope* spreads the light of a heavenly body out into its spectrum, a series of lines which can be studied to find the velocity, composition, and temperature. The upper diagram in Fig. 35 shows the objective prism type. A large prism over the end of the telescope spreads the light of all the stars out into short spectra. The lower spectroscope in the same figure is attached at the eye end of the telescope, with the image of the star falling at S. The upper instrument in Fig. 36 is similar, but uses a grating

instead of a prism. These instruments give long spectra of a single star. The lower instrument in Fig. 36 is a direct vision spectroscope, a small low-power instrument not attached to the telescope but held in the hand.

The *photometer* measures the amount of light received. The *spectroheliograph* photographs the Sun in the light of one element. The *spectrohelioscope* and the *monochromator* each give views of the eruptions on the Sun in the light of one element. The illustration on page 409 shows a photometer.

Location of Telescopes. Research telescopes, in general, should be located well away from the lights, smoke, and dust of a city. A hill, or elevated plateau, is an advantage, and placing the telescopes many feet above the ground level helps. In the United States, the West and the Southwest have many more nights which are good for astronomical work than other parts of the country.

Universities and colleges often mount an astronomical telescope half a mile, or a mile from the center of the campus. Too often, such a small observatory is soon surrounded by trees, buildings, and lights. Usually the distance from the center of the campus limits its value in teaching, and a large class can do little observational work with a single telescope. A battery of small telescopes is much better than a single larger telescope.

If one cannot get away from lights, dust, trees, and buildings, the next best thing is to get above them. The top floor of a science building near the middle of the campus, with equipment on the roof, is a good location.

Planetariums. The modern planetarium is a device for showing the heavens as they appear to the eye at night. The "sky" is a large dome which forms the ceiling of the room in which the audience is seated. In the middle of this circular room is an instrument carrying many projectors for picturing the Sun, Moon, planets and stars on the inside of this dome.

The planetarium projectors are mounted on an axis parallel to the Earth's axis (for any desired latitude) so that a simple rotation causes the pictures to rise, move across the "sky," and set, quite realistically. The planetarium can show the appearance of the sky for any place on the Earth, and for any day of any year from early history to far in the future, with reasonable accuracy.

The planetarium is an expensive instrument, and is useful for

FIG. 37. The Projector of the Griffith Planetarium. Photograph from Griffith Observatory

entertainment and for arousing popular interest rather than for teaching and research. There is no planetarium either privately owned or connected with an educational institution. There are five in the United States now (1942), all operated by public parks or by museums.

Exercises

1. What was the optical system of the first telescopes? What was the nature of Kepler's inprovement?
2. What is the magnifying power of a telescope whose focal length is 15 feet when using eyepieces with focal length (a) 3 inches, and (b) ½ inch?
3. When should low magnification be used? When should high be used?
4. What is the focal ratio of a telescope?
5. What is the focal ratio of the 40-inch Yerkes refractor if the tube is approximately 62 feet long?
6. Calculate the length from the mirror to the image for the 200-inch and the 100-inch telescopes, if the focal ratios are f/3.3 and f/5 respectively.
7. What are the two important functions of the telescope?
8. What are the defects of simple lenses and how are they overcome?
9. What are the two optical arrangements for big reflecting telescopes, and for what is each used?
10. What is the resolving power of a telescope? Distinguish from magnifying power.
11. If in a double-star system the stars are $0''.11$ apart, what aperture telescope is needed to separate them?
12. If the 200-inch telescope is used on double stars, what is the closest which can be separated under good conditions?
13. What are the technical difficulties which cause the failure of lenses larger than the 40-inch lens at the Yerkes observatory?
14. What are the essential differences between the reflecting and refracting types of telescopes?
15. What are the advantages and disadvantages of the reflecting telescope?
16. What is the latest advance in telescopes? Explain its principle.

17. Name and explain the various types of telescope mountings. What are the advantages of each?
18. What is a coelostat? Where are coelostats used?
19. What instruments are used in connection with, or attached to, the telescope?

☆ IV ☆

The Earth

Early people, in general, believed the Earth to be flat with the sky a sort of vault over it.

Greek Scholars Knew that the Earth is Round. The Greek philosopher and mathematician Pythagoras was one of the earliest known to have taught the spherical Earth. The scholar Aristotle, who lived from 384 to 322 B.C. was one of the first to state some of the proofs commonly given in geography that the Earth is round. Aristotle stated that the Earth is round because, when a ship is sailing to sea, the hull disappears before the mast and the sails; and because the edge of the shadow of the Earth on the Moon is always an arc of a circle.

The shape of the Earth is nearly spherical. This means that the curvature is nearly the same everywhere and in every direction. *Down* for every person on the Earth is the direction in which objects tend to fall, that is, approximately toward the center of the Earth. The fact that this direction is opposite for persons on opposite sides of the Earth should cause no difficulty. It is obvious that people who are on the opposite side of the world from those of us in the United States would walk with their heads in the direction which is down for us.

Proofs that the Earth is Round. The following are some of the fundamental proofs that the Earth is round:

1. *The disappearance of a ship at sea.* As a ship sails to sea, the body of the ship disappears first and the top of the mast last. Observation shows that a flag at a given height above the water disappears at about the same distance from the observer, whatever direction the ship is sailing and in whatever part of the World it happens to be.

2. *The edge of the shadow of the Earth on the Moon is always an arc of a circle.* As the edge of the shadow of the Earth crosses the Moon, it is always an arc of a circle as closely as can be seen. The only shape which casts a shadow such that all sections of the edge are arcs of a circle is a globe.

3. *Northern stars rise if we travel north and sink if we travel south.* It has been observed that for each 69 miles we travel north, the North Star rises one degree and for each 69 miles we travel south, the North Star sinks one degree. Since this apparent motion is the same for stars that are practically overhead as it is for stars near the horizon, it follows that the heavenly bodies must be situated at very great distances, so great that lines from them to different points on the surface of the Earth can be considered parallel in ordinary astronomical work. It follows also that the Earth must be curved uniformly in a north and south direction, and that a north and south section, at least, is circular.

4. *A level line is not straight, but curved.* When an engineer runs a level line, setting the tops of stakes level, a sighting from the first stake to the last shows that the line is not straight. The middle stakes are above a straight line joining the first and last. Measurements show that the curvature of a level line is practically the same all over the World and in every direction. The curvature is, of course, the same as that of the ocean, since the surface of the ocean is level.

5. *Photographs from great altitudes as from stratosphere balloons.* Photographs from great heights show the horizon to be curved, and the greater the height, the more the curvature. From the curvature of the horizon, a trained person can calculate the approximate size of the globe of the Earth. (See Fig. 38.)

6. *A navigator, calculating his position on the Earth by modern methods, assumes the Earth curved uniformly everywhere and in every direction.* The fact that for more than 100 years ships have been correctly located on this assumption every day and in all parts of the World is conclusive proof that the assumption is correct. The only figure which is curved uniformly everywhere and in every direction is a globe, and hence the Earth must be a globe.

7. *Many persons have gone around the globe keeping an approximately easterly or approximately westerly direction and have re-*

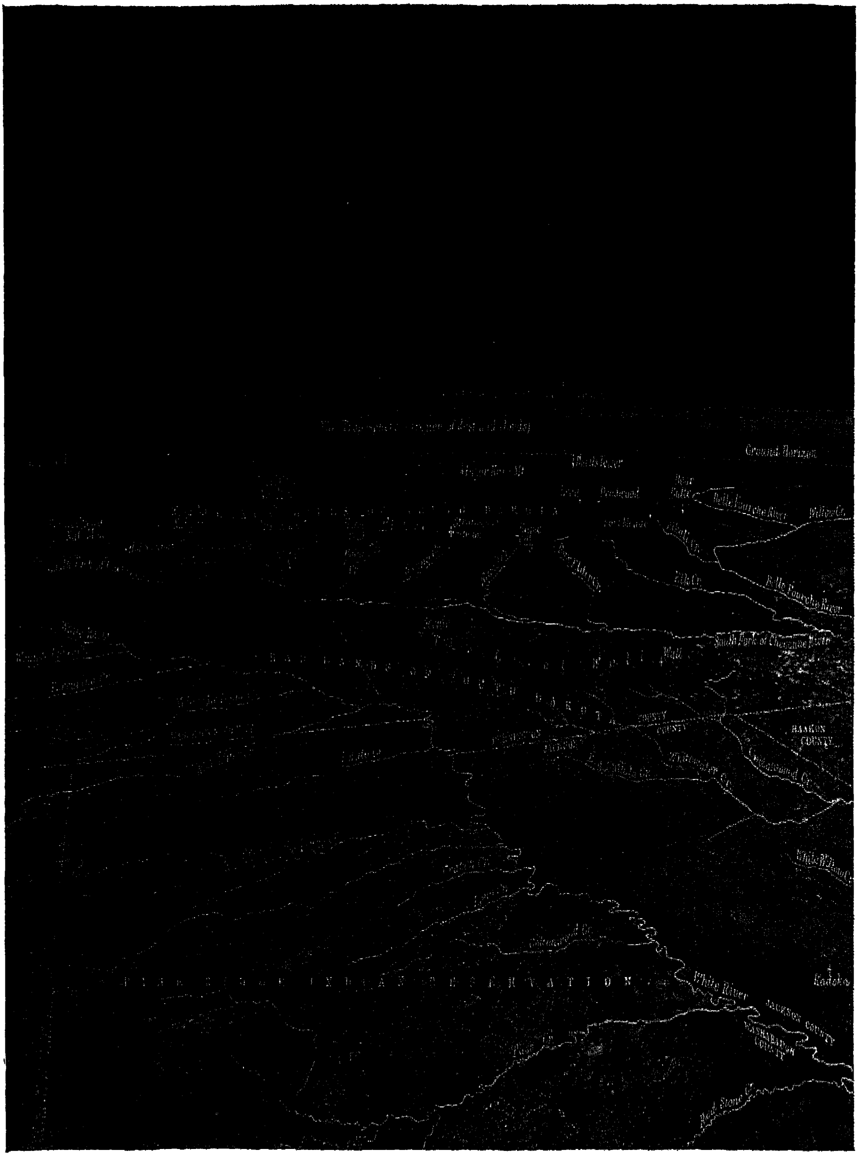


Fig. 38. The Curvature of the Horizon as seen from a height of nearly 14 miles. Photograph from National Geographic Society

turned to their starting points. This appeals to most people as a good proof that the Earth is round, but it was not considered much of a proof by some. They replied that men had sailed around England, and that did not prove that England is a globe.

Measuring the Size of the Earth. Knowing that the Earth is an oblate spheroid (see Fig. 39), we can determine the approximate size by measuring the number of miles, or kilometers, in a degree, or a given number of degrees. This requires two types of measurements: (a) the number of miles between two points (engineering); (b) the number of degrees between the same two points (astronomical).

One of the first scientific measurements of the circumference of the Earth was made by *Eratosthenes*, of Alexandria, Egypt, in the third century before Christ. He had observed that the Sun was directly overhead at noon at Syene on the longest day of the year, because there was no shadow at the bottoms of wells. He measured the angular distance of the Sun from the zenith as seen on that day from Alexandria, by measuring the length of a shadow cast by a *gnomon* (a vertical stick or shaft) of known length, and found it to be 1/50 of a circumference, or 7.2 degrees.

You have read that the heavenly bodies are so far away that lines to different points on the surface of the Earth can be considered parallel, for practical purposes. From a simple geometrical figure, and from the well known theorem that exterior and interior angles of parallel lines are equal, it follows that the distance from Syene to Alexandria is 7.2 degrees on the surface of the Earth. This is 1/50 of 360 degrees so Eratosthenes found that the distance from Syene to Alexandria must be about 1/50 of the entire circumference of the Earth. The accepted distance between the two cities was 5000 stadia, and hence the circumference of the Earth, according to Eratosthenes, was 250,000 stadia.

We do not know which stadium was used by Eratosthenes. The common Olympic stadium was 630.8 feet in length. It seems most probable that Eratosthenes was using that; and if so, his figure was 29,900 miles for the circumference of the Earth, or 9500 for the diameter. The correct figure for the mean diameter is 7918, so on this assumption, his result was too big by about 20 per cent.

The measurement of the angle by Eratosthenes was good, but

the adopted distance between the two cities was too large. Distances were measured in those days by professional pacers, and if the roads were not straight, the measured distance would be too large. Further, the places were not on an exact north and south line.

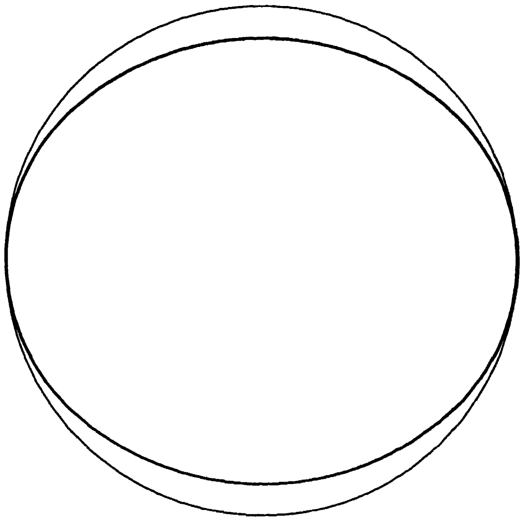


FIG. 39. An Oblate Spheroid Imposed on a Circle

A later determination of the circumference, made by *Posidonius*, gave 180,000 stadia, which was about as much too small as the figure of Eratosthenes was too large. This figure gives almost exactly 60 modern miles as the length of a degree, or one mile as the length of a minute of arc on the surface of the Earth.

Ptolemy, the great astronomer and geographer, adopted the figure of Posidonius for the circumference of the Earth, and because of his great authority that figure was used until after the time of Columbus.

The Size and Shape of the Earth. With modern engineering instruments, the length of the degree has been determined very carefully in many different latitudes. From this work not only the size but the shape of the Earth can be determined with accuracy. The Earth is an oblate spheroid as shown in Fig. 39, that is, sections parallel to the equator are circles, but sections through the poles

are ellipses. Because of its rotation, centrifugal force causes the Earth to bulge at the equator.

Modern figures for the length of the degree are, at the pole 69.41 miles, and at the equator, 68.71 miles. Modern figures for the Earth's diameter are:

Equatorial	= 7926.68	miles
Polar	= 7899.98	"
Mean	= 7917.64	"

It will be noticed that the mean diameter is not the average of the polar and the equatorial. This is because a solid body has three dimensions. In the case of the Earth, if we use as one dimension the polar diameter (7900), it is obvious that the other two dimensions are both equatorial diameters (7927). The average of the three dimensions 7900, 7927, and 7927 gives the mean of 7918.

Gravity. The Law of Gravitation, discovered by Newton, states that "Any particle of matter attracts any other particle with a force inversely proportional to the square of the distance between them, and directly proportional to the product of their masses." Denoting the force by F, the distance by d, and the masses by M_1 and M_2, the law may be written as a formula

$$F = k\frac{M_1 \times M_2}{d^2},$$

where k is a numerical factor, a constant, depending on the units employed.

Newton showed that if bodies are homogeneous spheres, or spheres composed of homogeneous concentric layers, they attract as though the matter were concentrated at the center. The Earth is so nearly spherical that in most work the equatorial bulge can be neglected.

Measuring the Mass of the Earth. The mass of the Earth can be determined from the law of gravity, by comparing the attraction of some known mass for an object with the attraction of the Earth for the same object.

Suppose the known mass is B, the object attracted is b, and the distance between the centers of gravity of B and b is r. Denote the radius of the Earth by R, the mass of the Earth by E, and the at-

traction of B for b by f. Then from the law of gravitation, the attraction f is

$$f = k\frac{B \times b}{r^2}.$$

The attraction of the Earth for b is simply its weight. Denote this by F, then

$$F = k\frac{E \times b}{R^2}.$$

If the attraction f and the distance r are measured, the factor k can be eliminated, and the only unknown in the two equations is the mass of the Earth E. Solving,

$$E = (BF/f)(R/r)^2.$$

The first determination of the mass of the Earth was made by comparing the attraction of the Earth with the attraction of a mountain. A later determination was made using a mine, and comparing the attraction of the whole Earth with the attraction of the outer shell. Neither of these methods was very satisfactory. The mass of the mountain was uncertain, and the mass of the effective outer shell was uncertain.

Because of the uncertainty in using big natural masses, scientists turned to the use of smaller masses in the laboratory. One method, which has given good results, is the use of an *accurate common balance*. The most recent work on the mass of the Earth has been done at the U. S. Bureau of Standards with a *torsion balance*. Two small gold balls were attached at opposite ends of a small stick suspended at its center by a quartz fiber. The force necessary to twist the quartz fiber a small amount was known. Heavy steel cylinders were mounted on a stick of the same length as that supporting the gold balls. The middle of the stick supporting the cylinders was placed directly under the quartz fiber. By turning one way the cylinders could be brought close to the gold balls, so that the pull of each cylinder on a gold ball tended to give the quartz fiber a twist to the left. By turning the other way the cylinders could also be brought close to the gold balls so that the pull on the gold balls twisted the quartz fiber in the opposite direction. The weight of

the gold balls was the pull of the Earth; the twist of the quartz fiber gave the pull of the cylinders for the gold balls. A simple calculation using the preceding formula gave the mass of the Earth. For accurate work the torsion balance equipment is mounted in a vacuum, so that air currents do not disturb the swinging of the gold balls supported by the quartz fiber.

The Mass, Density, and Rigidity of the Earth. From these measurements it has been found that the Earth is about 5.51 times as heavy as a ball of water of the same size would be. The weight in tons can be expressed by writing 66 followed by 20 ciphers, or as 6.6×10^{21}. The rocks at the surface of the Earth are about 2.75 times as heavy as water. Since the mean density is about double the surface density, the density in the interior must be much higher. It appears that at the center of the Earth the density is about 11 times that of water. Since the density of gold is about 19, it is evident that the interior of the Earth cannot have much gold. In fact, there cannot be much lead since the density of lead is about 11.4, which also is too high. But allowing for the enormous pressure, it appears that the center of the Earth might be iron. The density of ordinary iron is about 7.7 times that of water.

Near the surface of the Earth the temperature increases about one degree Fahrenheit for each 75 feet increase in depth. If this rate of increase continued for a few hundred miles, the temperature would be far above the melting point of rock. From laws of physics the same rate should not continue, but it has been estimated that the temperature near the center of the Earth may be as high as 5000°F.

Because of this increase of temperature with depth, and because of the molten materials thrown out by volcanoes, it was once thought that the interior was molten and only the surface layers were solid. The term "crust of the Earth" dates from this time. By about 1850, however, studies of leading scholars had convinced them that the Earth, as a whole, must be solid with no great portion of the interior molten.

That the Earth, as a whole, must be as *rigid as a steel ball* of the same size is shown by the tides. If the Earth were viscous rather than solid, tides would be raised in the body of the Earth itself. With the bottom and the shores of the ocean raised by the tidal effect, the level of the water would not change appreciably. The

fact that there is a tide shows that the Earth itself does not yield, as a liquid. From the amount the tides are piled up, it can be computed that the Earth must be as rigid as steel.

The ocean tides cannot be measured with accuracy because of the piling up on the shores of the continent. For a more accurate result closed tubes about 500 feet long were buried on the grounds of Yerkes Observatory, Williams Bay, Wisconsin. The tides in these tubes were measured with microscopes and from these measurements a more accurate value of the rigidity and elasticity of the Earth could be computed. Tides have been measured also in deep wells, for example at the University of Iowa, Iowa City, Iowa.

That the Earth, as a whole, is as rigid as steel is shown also by earthquake waves. The rigidity can be computed from the time the earthquake waves arrive at various stations as recorded on seismographs. There are two types of earthquake waves, and a study of records has shown that although the longitudinal vibrations pass through the nucleus, or the deep interior of the Earth, the transverse vibrations do not. Evidently the nucleus is not so rigid as the Earth as a whole.

The age of rocks can be determined from the fact that the rate at which uranium breaks down into certain types of lead is known. From the amount of uranium, and the amount of this type of lead, the time since the formation of rock can be calculated.

The age of the oldest rocks known is found in this way to be about 1,800,000,000 years. The age of the Earth itself may be only a little greater.

The Air

Early people did not understand that the air is part of the Earth. An argument against the rotation of the Earth was that, if the Earth turned, there would be winds of a thousand miles per hour at the equator. We know now, however, that the air is simply the outer layer of the Earth, and that its weight, or mass, is considerable.

The *mass of the atmosphere* can be obtained from its pressure, since the pressure is simply the weight. Multiplying the pressure per square inch (14.7 pounds at sea level) by the number of square inches in the Earth's surface, it is found that the mass of the atmosphere is 5.8×10^{15} tons. This is about one-millionth the total

mass of the Earth, as can be seen by comparing this figure with that derived on page 88.

Composition of the Atmosphere. The two chief gases in the atmosphere are nitrogen (nearly four-fifths) and oxygen (about one-fifth). The following table lists the more important gases.

TABLE V. COMPOSITION OF THE ATMOSPHERE

Nitrogen	(N)	= 78%
Oxygen	(O)	= 21
Argon	(A)	= 0.94
Carbon Dioxide	(CO_2)	= 0.03
Water-vapor	(H_2O)	= variable

Among the gases most important to human life are oxygen and carbon dioxide. Sunlight acting on chlorophyll, the green substance in plants, causes the carbon of the carbon dioxide to unite with the hydrogen of the water, brought up from the roots of the plant, to form carbohydrates. This process is called photosynthesis. The cxygen, from the carbon dioxide, is used in forming the carbohydrates, and that from the water, is given off, or exhaled, by the plant. At night the plants do take in a small amount of free oxygen. Animals use plants, or other animals, for their food, and so all life on the Earth is dependent, directly or indirectly, on the carbon dioxide of the air and the formation of carbohydrates in this way.

Animal life on the Earth is also dependent on the active chemical oxygen which makes up about a fifth of our atmosphere. Animals, especially in the higher forms, are distinguished by their ability to move about from place to place. The higher and more energetic forms of animal life can travel considerable distances from one source of food supply to another. The energy for this movement is released by breathing in free oxygen, which oxidizes the food the animal has eaten. It is essential that, as the animal moves about, there be plenty of free oxygen available at all times in the medium in which it is moving. On the Earth, free oxygen is available to an animal at all times whether he is moving about in the air or in the water. There is more oxygen available in the air, and perhaps this is the reason that air-breathing animals have developed to a higher plane than have water-breathing animals.

Height of the Atmosphere. (See Fig. 40.) The height of the atmosphere can be determined in several ways, and the results vary

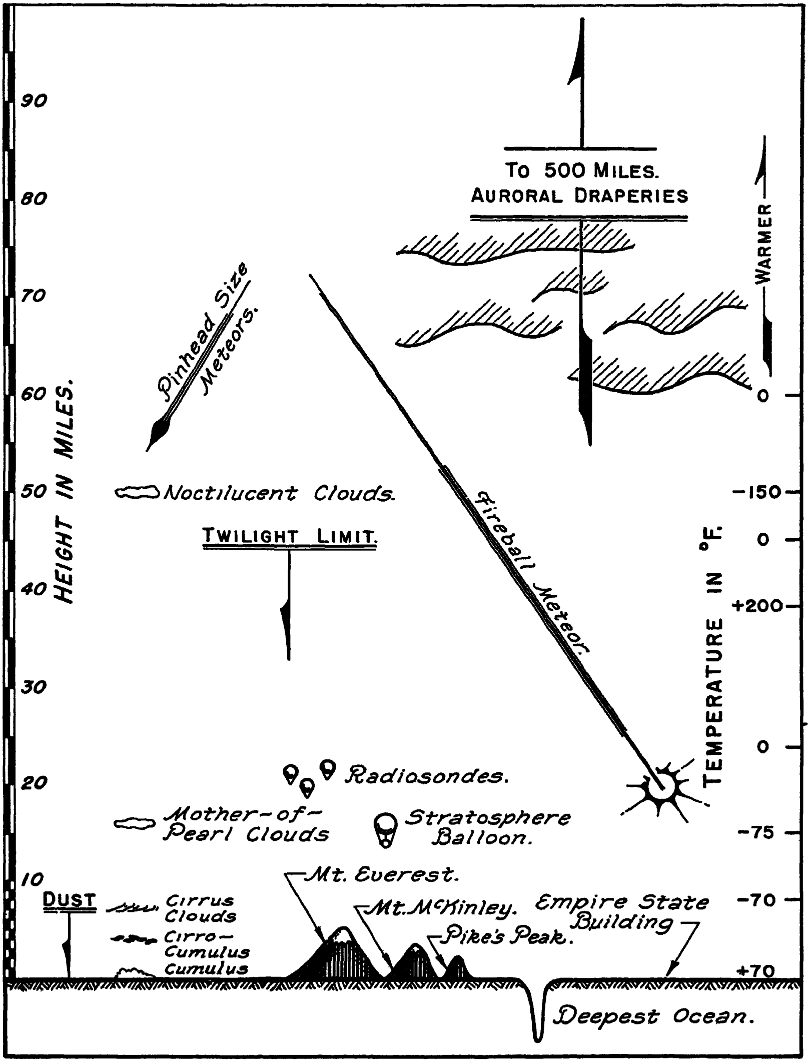


FIG. 40. The Height of the Atmosphere

depending upon the density of the air shown by that method. Some people think first of the height reached by stratosphere balloons or by radiosondes, the unmanned instrument-carrying balloons. A stratosphere balloon rose November 11, 1935, from Rapid City, South Dakota, and reached a height of nearly 14 miles. The radiosondes, or instrument-carrying balloons, have gone as high as 20 miles.

As another criterion, the height of clouds is taken. The very highest clouds, the noctilucent, are 50 miles high, and are always found surprisingly close to that height, neither higher nor lower. These clouds show that there is sufficient air to float them at that height.

Observation of the twilight glow shows that there is sufficient air to reveal this glow at a height of 50 miles.

Meteors are little particles falling into the Earth's atmosphere from outer space. As they enter the upper space at a very high speed, the molecules of air knock off particles which shine. Many meteors are observed to appear at heights of 70 miles, and more doubtful observations give heights up to 100 miles. The observations of meteors show that there is sufficient air to cause the shining of meteors at 70 miles, and possibly at 100.

The auroral streamers are a glowing of the rarefied nitrogen and oxygen in our upper atmosphere, similar to the glowing of rarefied gases in a vacuum tube. At times of especially strong disturbances, auroral streamers have extended as high as 500 miles. These streamers show that there is some rarefied gas at that distance above the ground.

The law of change of density with height is such that half of the atmosphere is within 3½ miles of the Earth's surface, half of what remains is within the next 3½ miles, and so on as long as the air behaves as a gas.

Refraction. When light passes from one medium to another, it is bent according to a well-known law of optics. The amount of bending, or refraction, depends on the density of the medium through which the light is passing. In Fig. 41 light is bent as it passes through a glass prism. The density of the atmosphere is only that of a fair vacuum at a height of 100 miles above the surface of the Earth while at a height of 3½ miles the density is half that at sea level. Consequently, when light from a heavenly body reaches

the observer's eye, most of the bending is in the lower part of the atmosphere. The total amount of the refraction depends on the density of the air at the surface and on the angle at which the light entered. For an object at the zenith the bending, or refraction, of the light ray, of course, is zero. For an object 10° from the zenith the refraction under average conditions is 10″ of arc, that is, an object appears that much above its true position. For an object on

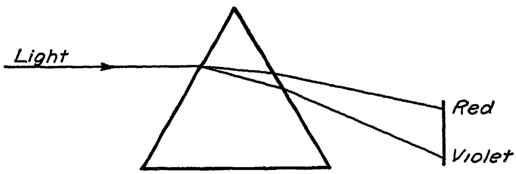


FIG. 41. Refraction of Light by a Prism

the true horizon the refraction under average conditions is 34′, or more than the apparent diameter of the Sun. Hence, when the Sun appears just above the horizon, in reality it is just below the horizon. (See Fig. 42.)

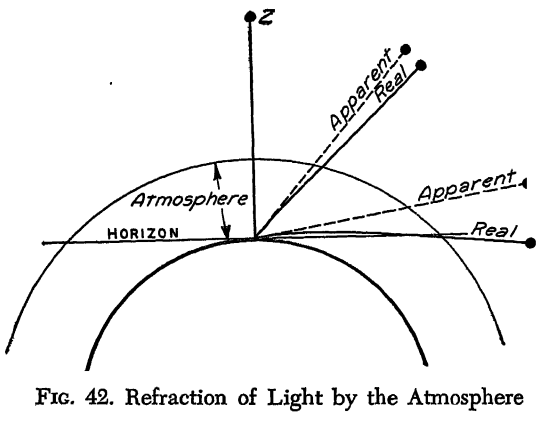


FIG. 42. Refraction of Light by the Atmosphere

Sunrise and Sunset. The time of sunset is defined legally as the time of disappearance of the upper edge of the Sun for a level horizon, that is, for a horizon unobstructed by buildings, trees, or hills. The time of sunrise is defined, in the same way, as the time of appearance of the upper edge of the Sun above a level horizon.

In other words, the Sun has risen as soon as any of it can be seen above a level horizon, and it has not set until all of it has disappeared below a level horizon. The times of sunrise and sunset, for an average refraction, can be taken from tables in the *American Nautical Almanac* or the *American Air Almanac* for any longitude and latitude and for any date.

Twilight. The glow after sunset, known as twilight, is due chiefly to the reflection of sunlight from the upper layers of our atmosphere. Immediately after sunset the air and the clouds over us are still in full sunlight, and this sunlight is reflected and scattered so that it illuminates the landscape, at first quite efficiently. As the Sun sinks lower, the clouds and the air over us are no longer in the sunlight, but in the west the upper layers of the air, still in full sunlight, continue to reflect and scatter sunlight so that the western sky appears bright. In the early morning before sunrise, the eastern sky is illuminated in exactly the same way, and this glow is also called twilight, or, specifically, *dawn.*

Astronomical twilight lasts until the faintest stars can be seen or as long as there is an appreciable twilight glow. There is an appreciable twilight glow until the Sun is 18° below the horizon, so astronomical twilight ends then. The time of ending of astronomical twilight, or beginning of dawn, for any latitude and for any date can be taken from the *American Nautical Almanac.*

Civil twilight includes the period in which ordinary outdoor activities can be carried on without artificial light in clear weather. In latitude 40° this is about 30 minutes after legal sunset. The law requires that car lights be turned on 30 minutes after legal sunset and kept on until 30 minutes before legal sunrise. The *Air Almanac* defines civil twilight as ending when the Sun is 6° below the horizon, and includes tables from which the duration of civil twilight can be found for any latitude up to 60° and for any date.

Twinkling of Stars. The chief cause of the twinkling of the stars is the fact that irregularities in the atmosphere concentrate the light in some places and turn it away from other places. By letting the light of a bright star shine through an open window on a white sheet, light and dark mottlings similar to those on the bottom of a rippling pool, can be seen moving across the sheet. As one looks at a star, these light and dark mottlings move across its face, and

the image of the star seems to move back and forth slightly, and to grow brighter and fainter, in other words, to twinkle.

In the winter time if sunlight is allowed to shine into a warm room through an open window, there are pronounced irregularities at the window, where the warm air of the room meets the cold air of the winter day outside. These irregularities produce light and dark mottlings which can be seen moving across a white sheet illuminated by sunlight coming through the open window. These mottlings are not seen ordinarily in sunlight, however, for the usual irregularities are too far from the illuminated surface. At a distance of 110 feet from such irregularities, the light mottling from one edge of the Sun would be a foot from the light mottling from the other edge of the Sun. Since the usual distance apart of the light and dark mottlings is less than a foot, the light mottlings from one part of the Sun would fall on the dark mottlings from another and produce a uniform illumination. Hence, in ordinary sunlight no mottlings are noticeable.

At the time of a total eclipse of the Sun, however, just before the Sun is covered, the bright edge becomes for practical purposes a line. Just at the end of totality the edge of the Sun reappearing is again, for practical purposes, a line. This line of light means that the mottlings will overlap in one direction but not in the other and produce what are called *shadow bands.*

Although the planets are points of light as far as the naked eye is concerned, the disk is wide enough to offset the effect of twinkling. Many of the irregularities in the density of the air are high enough to cause an appreciable overlapping, and hence, elimination of the mottlings. So planets twinkle less than stars at the same altitude.

The twinkling of the stars, which causes an appreciable change in the position of the stars as well as in their brightness, interferes with astronomical work. In visual work it is difficult to measure accurately the position of an object that is jumping about, and in photographic work this jumping about causes the image of a star to appear as a disk rather than as a fine dot.

The Zodiacal Light. On clear moonless nights in the Spring, as the twilight glow ends, what appears to be a cone of soft hazy light with its base on the western horizon, and its vertex often near the Pleiades, is conspicuous in the western sky. Keen observers

FIG. 43. The Zodiacal Light, March 17, 1928. Photograph from Yerkes Observatory and University of Chicago Press

working under good conditions, especially in the tropics, see this light, which has been named zodiacal light, both in the evening and

FIG. 44. Aurora Borealis, September 18, 1941. View near Zenith. Photograph by Frank M. Preucil

morning sky. Under the best conditions, it has been observed to extend completely around the ecliptic, with a definite increase in

light near the point opposite the Sun. This elongated patch of faint hazy light, at the point of the ecliptic opposite the Sun, is called the *gegenschein.* The gegenschein, or counterglow, is so faint that the average astronomer looks for it only rarely, and it cannot be photographed. However, with a modern photoelectric photometer the boundaries of the faint hazy spot can be mapped with accuracy. Fig. 43 shows the zodiacal light.

An explanation which appears to fit the observed facts is that the zodiacal light is reflected from swarms of meteoric particles which are revolving about the Sun nearly in the plane of the ecliptic, that is, approximately in the plane in which the Earth and the other planets revolve. This swarm appears to be shaped like a convex lens thickest about the Sun, and thin near the outer edge. Calculations indicate that such particles would be concentrated at a point in the direction opposite to the Sun at a distance from the Earth of nearly a million miles. The combined attraction of the Earth and the Sun would cause a sort of a dynamic whirlpool at that point, which we see as the gegenschein.

Auroral Displays. Observations show that auroral displays are more frequent in years of many sunspots. Also, when large sunspots cross the center of the Sun's disk, disturbances to radio, telephone, and telegraph occur. This agreement in time indicates that something on the Sun, or something coming from the Sun, is responsible for the aurora and for these disturbances. Studies have indicated that electrical particles thrown out from the disturbed areas on the Sun cause the rarefied upper air to glow like the rarefied gases in a vacuum tube. As these particles from the Sun come into the Earth's atmosphere, they enter along the lines of force of the Earth's magnetic field. These lines of force are parallel, or nearly parallel, to the surface of the Earth in equatorial regions. Hence, few electrical particles get into the atmosphere and there are few auroral displays in those latitudes. In latitude 40°, the lines of force are within less than 20° of the perpendicular, so auroral displays are not uncommon. Farther north where the lines of force are more nearly vertical, the displays are even more common.

As the auroral streamers are parallel to the lines of force, which in turn, are within a few degrees of the vertical, the auroral streamers, as seen in most of the United States, point in a general way toward the zenith. These streamers are a greenish white or

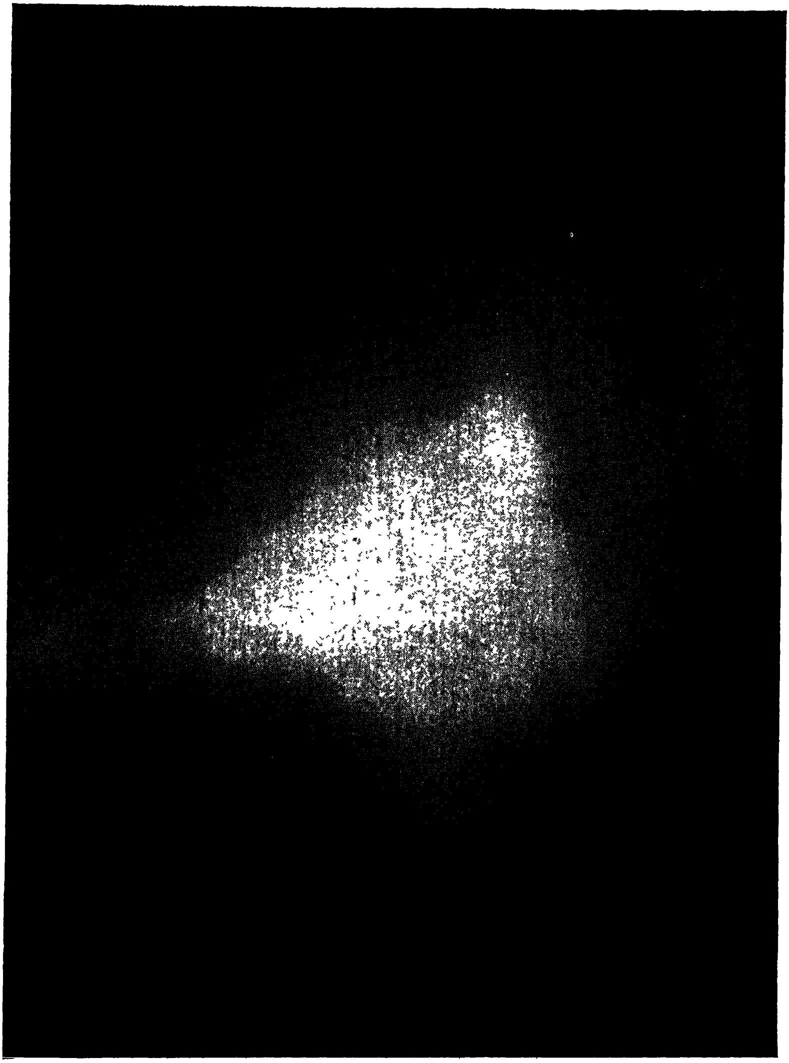


Fig. 45. Aurora Borealis, September 18, 1941. Photograph by Frank M. Preucil

sometimes a pearly gray in color. Occasionally, but usually for only a short time, the streamers turn a rosy pink in color. The streamers radiate from a low arch in the northern sky, and below this arch the sky is glowing with a peculiar purple tinge. This purple color low in the north is one of the best tests as to whether or not there is a faint auroral display. One of the tests of whether a streamer is auroral or not is its relatively rapid motion. In an active auroral display streamers show pulsations or apparent motion along the streamer. There also is definite and often rather rapid motion from side to side. The accompanying photographs show the auroral display of September 18, 1941.

The auroral clouds are an interesting phenomenon. These are faintly luminous clouds resembling small cumulus clouds. They form and increase in size rapidly. They may fade away with corresponding rapidity, but in general, show no lateral motion or drift. In these characteristics they are different from the water-vapor clouds seen at night. Water-vapor clouds, if watched for a time, show little appreciable change in appearance but do show a slow lateral motion or drift.

The most accurate measurements of height have been made by the Norwegian observer Störmer, who photographed the displays from two stations separated by 20 or 30 miles. The real height can be calculated with accuracy from the photographs made at the two stations. At times of particularly brilliant displays, the very highest streamers reach a height of about 500 miles.

Careful studies of the night sky indicate that on a clear moonless night only about one-sixth of the light comes from the stars. The remainder is due to a permanent auroral illumination and to the zodiacal light. With large spectroscopes the auroral lines can be photographed on any clear moonless night as far south as Arizona.

Halos and Coronas. There are two common rings seen about the Moon, or about the Sun. The first is the halo formed by ice crystals, usually snow. This ring is brilliant in color, with the red on the inside. The radius of the ring is 22°, which means that the distance from the Moon, or the Sun, is about the distance from the tip of the thumb to the tip of the little finger when the hand is held at arm's length with the thumb and fingers extended.

The second ring is the corona, due to droplets of water. The larger the droplets of water are the smaller the ring. Usually, the

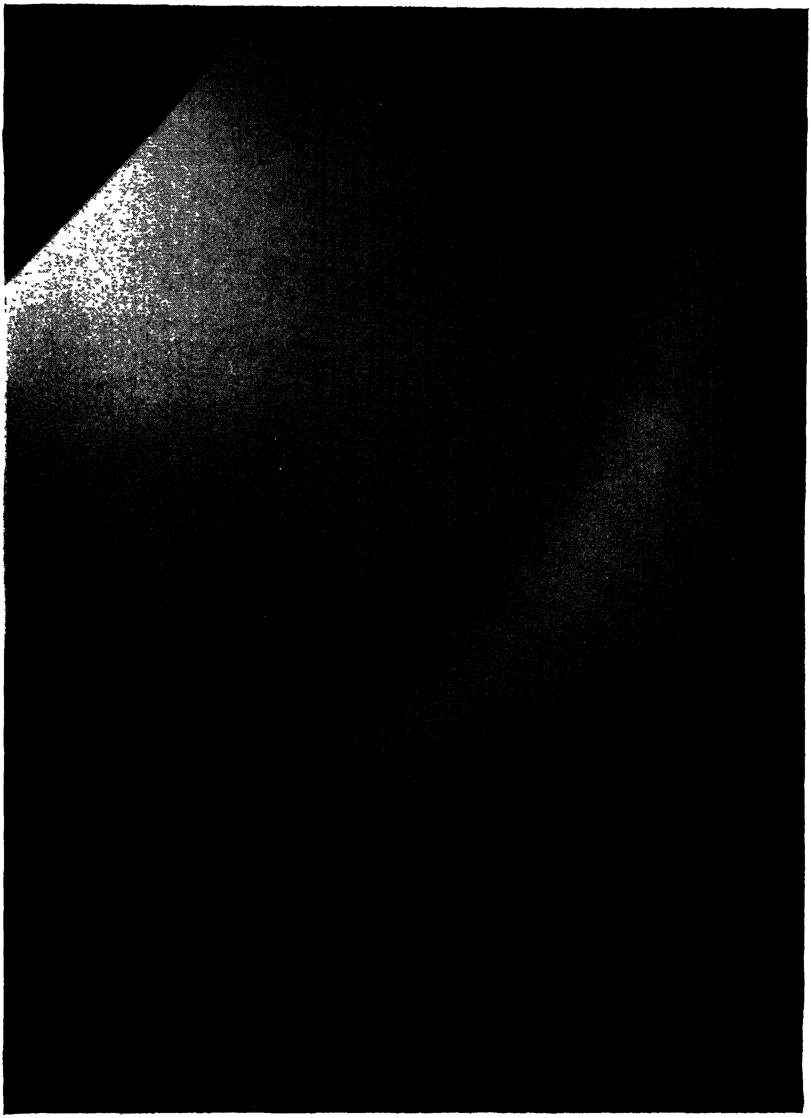


Fig. 46. A Solar Halo in Cirrostratus Clouds. Photograph from Lowell Observatory

droplets are of various sizes producing rings of various sizes which overlap, making a broad hazy ring with little coloring. If the droplets are of uniform size, however, the brilliancy of coloring may be almost equal to that of the halo, but the red is on the outside. This difference in the order of the colors makes it possible to distinguish at a glance the corona produced by water from the halo produced by ice crystals or snow.

The corona nearly always is much smaller than the halo. In fact, some of the most brilliantly colored coronas are so small that two fingers held side by side and at arm's length would cover the ring completely. The smaller size of the corona, perhaps only a tenth the diameter of a halo, usually makes it possible to recognize a ring as a corona at a glance. Although the size of the corona depends on the size of the droplets of water forming it, often the diameter of a corona changes appreciably in half an hour. If the ring is getting smaller, the droplets of water are getting larger, and this means that rain may fall soon. On the other hand, if the diameter of the ring is getting larger, the droplets of water are getting smaller, suggesting fair weather.

Sundogs and Moondogs. When there are ice crystals—that is, snow—in the air in sufficient quantity to produce a brilliant halo, the main ring of 22° radius is only a part of the complete pattern, especially if the Sun or Moon is low in the sky. There is a horizontal ray, or line of light, and a vertical ray, and there are other rings tangent to this main ring at points on a level with the Sun or Moon and directly above or below. When the Sun or Moon is low, light from the horizontal ray and from the tangent rings will be added to the light of the main ring producing the so-called *sundog* or *moondog* 22° from the Sun or Moon.

Mirage. A mirage is produced by a layer of heated air just above the sands of a desert, or above a pavement. This layer of hotter air reflects light striking at a low angle, just as water reflects. As a person is approaching such a place, the mirage area appears as a pool of water in which objects such as trees, signboards, or approaching cars can be seen. A color photo of the well-known Bonneville salt flats in Utah (where automobile speed records have been made) shows a mirage which makes the flats look like a lake.

Although relatively few have the opportunity to see the mirage in

FIG. 47. A Pavement Mirage

the western deserts, everyone has plenty of opportunities to see pavement mirages. Fig. 47 shows the headlights of an approaching car reflected in a pavement mirage.

EXERCISES

1. Name some Greek scholars of antiquity who believed the Earth to be round.
2. List and explain the proofs that the Earth is round.
3. Draw a diagram showing the geometry of Eratosthenes' method of measuring the circumference of the Earth.
4. Using 69 miles as the length of the degree, calculate the circumference of the Earth.
5. What is the mean diameter of the Earth, and how is it obtained from the equatorial and polar diameters?
6. Find the gravitational pull of the Earth on the Moon if the Moon's mass is equal to 1.6×10^{23} pounds, and the distance of the Moon is 60 radii of the Earth.
7. Assuming the mass of the Earth is 1.3×10^{25} pounds, and its radius 3960 miles, calculate the gravitational attraction of a 30,-

000-ton ship for a one-pound object at a distance of 1000 feet from the center of mass of the ship.

8. What is the rigidity of the Earth and how is it determined?
9. What is the approximate age of the Earth as computed by geologists?
10. What is the pressure per square foot of the atmosphere at sea level?
11. What are the chief constituents of the atmosphere? How much carbon dioxide is there? How does it compare with the amount of oxygen?
12. How is the height of the atmosphere determined?
13. Define refraction. Explain why we can see the Sun after it has really set.
14. Take from the *American Nautical Almanac,* or the *American Air Almanac,* the time of sunset and sunrise for your latitude and longitude for the coming week and check your calculations by an actual timing of sunrise or sunset over a good horizon.
15. Explain zodiacal light, aurora, and gegenschein.
16. How can one distinguish a halo from a corona?

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The Motions of the Earth

The Earth Rotates

The educated Greeks, as you have read, knew the approximate size of the Earth. They had no conception, however, of the size and distance of the Sun, planets, and other heavenly bodies. From the fact that the Sun, Moon, and stars rose in the east and set in the west it was evident to them that either the Earth turned to the east, or the heavenly bodies literally rose in the east and set in the west. They knew that either motion would explain the appearances; but, as we have said, they knew the Earth was big and solid, and they accepted the small and light appearance of the heavenly bodies as real. Since they believed the Earth bigger than the Sun, or other heavenly bodies, it seemed more reasonable to assume that the heavenly bodies moved, than that the Earth turned.

There was one important exception to this general opinion. The Greek scholar Aristarchus (earlier part of the third century B.C.) made a determination of the relative distance of the Sun and Moon, and obtained some conception of the great distance and size of the Sun. As a result, he came to the conclusion that the Sun was at the center of the solar system, and that the Earth was merely one of the planets going about the Sun.

Other Greek scholars did not have Aristarchus' realization of the size and distance of the Sun, even though they used some of his work. To them the stationary Earth and revolving Sun seemed more reasonable.

Proofs that the Earth Rotates. Rotation may be defined as a turning on an axis with respect to a relatively fixed system of coordinates or lines. The following are some of the simple proofs that the Earth rotates, or turns on an axis with respect to a set of lines

which remain fixed with respect to the stars. The *Foucault pendulum* experiment was first carried out by Foucault, in Paris, in 1851. A pendulum tends to swing in the same plane, just as any moving body tends to keep moving in the same direction. At the poles, an elevator shaft would turn completely around under a swinging pendulum in 24 hours. At the equator, the elevator shaft would be dragged eastward with no turning. Between the poles and

FIG. 48. The Foucault Pendulum. Photograph by F. W. Kent

the equator, there would be some turning and some dragging eastward.

Suppose, for simplicity, that the pendulum is set swinging in a north and south line, along the tangent *ac* in Fig. 49. Some time later the rotation of the Earth will have carried the pendulum from point *a* to point *b*. The pendulum will still be swinging in the direction *ac*, while the north and south line is now *bc*. The direction relative to the elevator shaft will have changed by the angle between *ac* and *bc*, that is by *acb*, while the Earth has rotated through *aob*. The rate of rotation of the pendulum is to the rate of

rotation of the Earth as *acb* is to *aob*. Considering the angles small, we can write

$$acb = ab/ac, \text{ and } aob = ab/ao,$$

whence

$$acb/aob = ab/ac \div ab/ao = ao/ac,$$

and

$$ao/ac = \sin acO = \sin aOA = \sin \text{Latitude}.$$

Hence, the rate of rotation of the pendulum divided by the rate of rotation of the Earth is equal to the sine of the latitude.

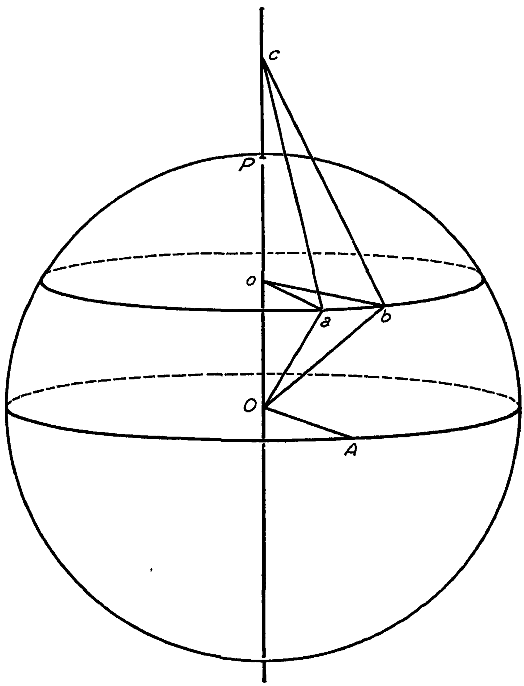


FIG. 49. The Theory of the Foucault Pendulum

Foucault, in 1852, carried out another experiment showing the rotation of the Earth by means of the *gyroscope*. A gyroscope may be thought of as a large top, with its axis horizontal. Because of

angular momentum, the axis of the gyroscope tends to remain in its original direction, and as the Earth rotates, it swings into a north and south line over the Earth's axis. The fact that the *gyroscope points north and south* is a proof of the Earth's rotation.

As a result of this experiment it occurred to Dr. Auschutz-Kämpfe that a compass could be constructed, using a gyroscope instead of a magnetic needle. This was developed during World War I and gyroscopic compasses were purchased for practically all fighting ships of the U. S. Navy.

The bulge of the Earth at the equator, or the fact that the Mississippi River flows south, is a proof of the Earth's rotation. The mouth of the Mississippi River is several miles farther from the center of the Earth than is its source. If the Earth were not rotating, the Mississippi River would flow north.

If the Earth were not turning, objects dropped would fall directly toward the center of the Earth. With the Earth turning, however, objects are thrown in the direction of turning. An *object dropped* from the top of a mineshaft is *deflected eastward* as it falls. In northern latitudes there is an appreciable southern deflection, from centrifugal force. The fact that the eastward (and southward) deflection can be observed is a proof of the Earth's rotation.

In the Northern Hemisphere *currents of air or water* moving northward are going from more rapid to slower motion, and so *are deflected* to the east, or right. (See Fig. 66, page 148.) Currents moving southward are moving from slower to more rapid motion, and tend to lag behind, resulting in a *deflection* to the west, or right. The effect on air currents or winds is discussed under the next heading.

Projectiles from big guns, as the Paris gun of World War I, are deflected to the east when fired northward, and to the west when fired southward, in the Northern Hemisphere. They are deflected to the right in the Northern Hemisphere, just as currents of air or water.

Cyclonic storms rotate counterclockwise in the Northern Hemisphere and clockwise in the Southern. You have read that, in the Northern Hemisphere, currents moving northward are deflected to the east, and currents moving southward are deflected to the west. This deflection means that when air currents meet in the Northern Hemisphere, a counterclockwise whirl results. In the Southern

Hemisphere, the deflection is the reverse, and so the whirl is clockwise. (See Fig. 66, page 148.)

The large cyclonic storms moving across the United States regularly from west to east show this rotation. Hurricanes and tornadoes rotate counterclockwise also in the United States. Tornadoes are large enough "whirls" to start always at the cloud level, and show this effect. The smaller "whirlwinds" seen on the farms in Summer may turn either way. They start at the ground level from more local currents.

The *rising and setting* of the heavenly bodies shows that either the *Earth must turn on its axis*, or the heavenly bodies must revolve about it. The Greeks thought the Earth larger than the heavenly bodies, so they preferred to consider the Earth stationary. We know that the Sun must be big enough to hold more than a million Earths. This can be determined without assuming that we know whether the Earth turns or the Sun moves. Since the Sun and the other heavenly bodies are very big, it is reasonable to suppose that the Earth turns.

Constancy of the Earth's Rotation. The rotation of the Earth produces a motion at the equator of about 1000 miles per hour, or about 1500 feet per second. This motion of rotation is more uniform than any timepiece, because it is more nearly frictionless than anything which man has been able to construct.

The rotation, however, is affected by a small amount of friction, which is due chiefly to tides. The attraction of the Sun and Moon produces tidal bulges on the oceans, and as the Earth turns underneath this tidal wave, there obviously is friction. Because of the enormous size of the Earth, the friction has less effect than the average person might assume. Calculations indicate that the tides are doing work, or retarding the Earth, at the rate of 1,877,000,000 horsepower; but this enormous amount of work would decrease the time of rotation, that is, lengthen the day, only by about a second in 150,000 years. The movement of the Earth and other planets about the Sun, and of the Moon about the Earth, is frictionless, for practical purposes, even more so than the rotation. So observations of these motions can be used to check whether the rate of rotation is slowing down.

The eclipses of the Sun furnish the best check on the length of the day. There are reasonably good records extending back for

some 2000 years, and a discussion of these indicates a lengthening of the day at the rate of about a second in 100,000 years. Transits of Mercury and Venus furnish accurate checks on the position of those bodies with respect to the Earth and Sun, and a study of these has shown slight changes, in close agreement with the result indicated by eclipses.

To summarize, calculation indicates that the day should lengthen at the rate of about *a second in 150,000 years*, as a result of the tides. A study of eclipses indicates that it is lengthening at the rate of *a second in 100,000 years*. The agreement is satisfactory.

Time. The rotation of the Earth provides us with a natural clock which is more uniform than any which man can construct.

A *sidereal day* is the interval between two successive passages of a star across the meridian. More exactly, it is the interval between two successive passages of a point among the stars, the *vernal equinox*, across the meridian. The sidereal time at any instant is the right ascension of the meridian. Because of the convenience of this relationship, and the uniformity of the sidereal day, most astronomical clocks are regulated to keep sidereal time.

An *apparent solar day* is the interval between two successive passages of the Sun across the observer's meridian. Since the Earth moves about the Sun, the solar day is longer than the sidereal. In the course of a day the Earth has gone forward about a degree, so that it must turn about a degree extra to bring the same meridian under the Sun. Since the apparent solar days are not all of the same length, astronomers have adopted a *mean solar day*, and have calculated the amount by which the Sun is ahead or behind what it would be if its motion were uniform. Mean solar time is merely apparent solar time corrected for the variation from uniform motion. (See Fig. 103, page 233.)

The Earth Revolves

Early peoples had observed the stars in the morning sky just before dawn, and then watched the Sun as it rose. Knowing the star picture well, they could place the Sun on it with reasonable accuracy, and in that way they marked the apparent annual path of the Sun among the stars.

Greek scholars recognized that this apparent motion of the Sun among the stars could be explained, either by a motion of the Sun

about the Earth, or by a motion of the Earth about the Sun; but as you have read, they thought the Earth much bigger than the Sun. It seemed more reasonable to assume that the apparently small Sun moved about the Earth than to assume that the big solid Earth itself moved. The scholar Aristotle, in the fourth century before Christ, reasoned also that if the Earth were in motion about the Sun, the stars would seem to move with respect to one another. In this, he was correct, but the apparent motion of the stars as a result of the Earth's motion is much too small to be observed without the aid of a telescope.

Aristarchus, as you have read in the paragraphs on rotation of the Earth, had a better conception of the size and distance of the Sun, and he accepted the revolution of the Earth about the Sun. Aristarchus was practically alone in this belief in classical times, however. The other Greek scholars followed Aristotle in accepting the stationary Earth.

Proofs that the Earth Revolves about the Sun. With the information at hand in the days of the Greeks, even the most intelligent and best informed might well believe in a stationary Earth. In modern times, however, especially with information obtained by the telescope, we have many proofs that the Earth, not the Sun, moves.

This movement of the Earth about the Sun is revolution. Rotation and revolution often are used loosely as meaning the same thing, but in this work they must be defined strictly. Rotation, as you have read, is turning on an axis. When a wheel is whirling it is rotating, and the turning of the Earth on its axis is rotation. Revolution is a movement in a path around some relatively fixed point. The annual motion of the Earth about the Sun is revolution. The following are some of the more important proofs that the Earth revolves.

Aberration of starlight was announced by Bradley, one of the early directors of the Greenwich Observatory, in 1727. If a person is outdoors in a rainstorm, and the rain is falling vertically, he should hold his umbrella vertically to keep his clothing dry. If he is walking rapidly, however, he must tilt the umbrella in the direction in which he is moving to protect his knees. (See Fig. 50.)

In the same way, if an astronomer is observing a star and measuring its position with accuracy, the telescope must be tilted in the

direction of the Earth's motion as in Fig. 51. The tilt is in opposite directions at intervals of six months, since the direction of motion of the Earth changes every six months. The difference in the two directions of tilt of the telescope is 41 seconds, not quite enough

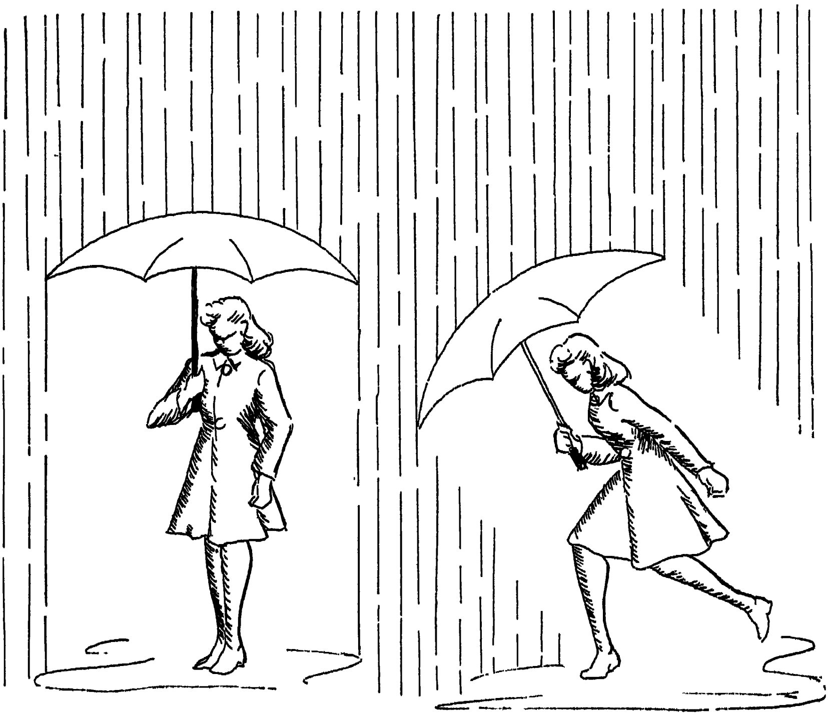


FIG. 50. Aberration Illustrated by Rain

to be detected with the naked eye even with keen eyesight, so it was not discovered until after the invention of the telescope.

Parallax can be defined as the difference in direction of an object seen from two different points. It can be illustrated simply by holding a pencil in front of the eyes and looking at the pencil first with one eye and then with the other. As this is done, the pencil will seem to move back and forth against the background of more distant objects, as for example, against the wall of the room. Before the days of the telescope, the fact that no such displacement could

be observed for the stars seemed to be a good argument against the revolution of the Earth about the Sun.

Parallax of the stars was observed, first in 1838 by the German astronomer Bessel, and in the next year by the English astronomer

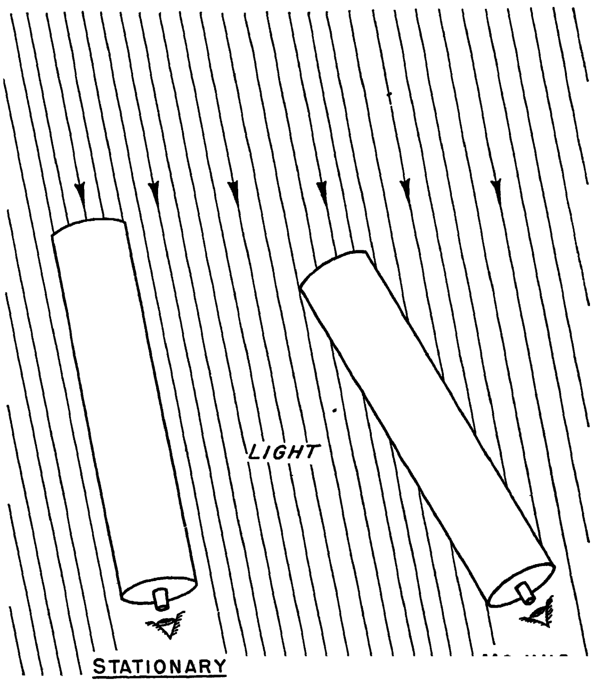


FIG. 51. Aberration of Light

Henderson. (See Fig. 52.) Since that time, the parallax has been measured for literally hundreds of stars, although extremely accurate work is necessary to detect this small change in position. Modern parallax work is equivalent to measuring by sight at a distance of six feet the amount a man's beard grows in five minutes.

The *spectroscope* measures the velocity with which a source of light is relatively approaching or receding. By *observing the stars with a spectroscope,* the relative velocity of approach or recession can be measured. In this way it is found that if stars on the ecliptic are observed when on the meridian at about 6:00 in the morning and again when they are on the meridian at about 6:00 in the

evening, the difference in velocity of the same stars is about 37 miles per second. The relative velocity of the same stars is 37 miles per second more of approach when observed in the morning than

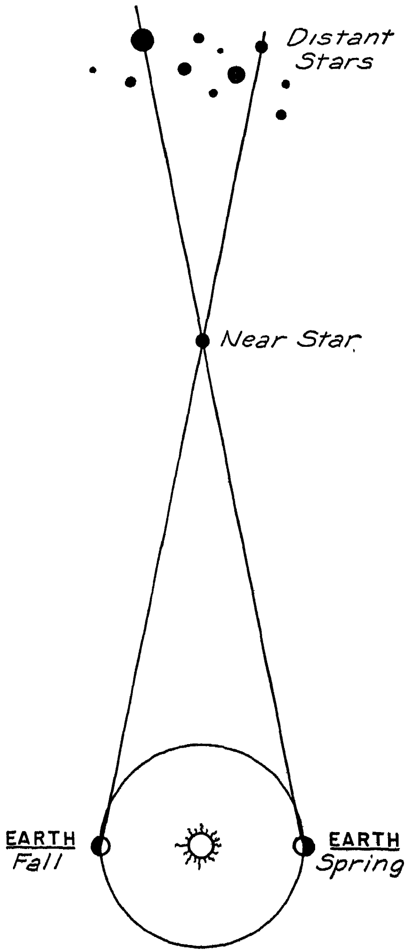


FIG. 52. Lines of Sight from the Earth to a Star Showing the Effect of Parallax

when observed in the evening. These velocity measurements can be carried all the way around the ecliptic, and the only reasonable interpretation is that the Earth is moving in the direction of the

stars on the ecliptic and on the meridian in the morning, with a velocity observation of about 18½ miles per second. This point toward which the Earth is moving is called the *apex*. The velocity observations not only show that the Earth moves in an orbit, but they give the size of the orbit. This proof dates from 1890.

Brandes announced, in 1827, that the *relative number of morning and evening meteors, and of autumn and spring meteors* proves the revolution of the Earth. Meteors are little particles which the Earth strikes as it moves along in its path about the Sun. If the Earth were stationary, we would expect meteors to strike on all sides in approximately the same numbers. Certainly we would expect no regular annual change in direction from which the meteors come. If the Earth is in motion, however, we would expect more meteors to strike on the front side, whatever the direction of the Earth's motion.

By looking at a model which shows both the motion of the Earth about the Sun and the rotation of the Earth, it can be seen that the morning side of the Earth is in front and evening side in the rear at all times. It can be seen also that in our Autumn the Northern Hemisphere is predominantly to the front.

From this observation it appears that if the Earth is in motion, there should be more morning meteors than evening meteors at all times of the year, and for both hemispheres more meteors should be observed in Autumn than in Spring. That is, in the Northern Hemisphere there should be more meteors in the months about its autumn equinox, August to November inclusive. In the Southern Hemisphere there should be more meteors observed in the months about its autumn equinox, that is, February, March, and April.

The observed numbers of meteors in both hemispheres are what would be expected with the Earth in motion. There are about three times as many morning meteors as evening meteors, and nearly three times as many autumn as spring meteors. The observed facts are what a moving Earth would produce, and not at all what a stationary Earth would produce. Observations of meteors give the *apex* of the Earth's motion, but they do not give the velocity of its motion, as spectroscopic observations do.

The Sun's apparent motion, plus knowledge of its size and distance is still another proof. The Sun's apparent motion among the stars was known in classical times, but this in itself is not proof of the revolution of the Earth about the Sun. As you have read previ-

ously, Greek scholars, in general, assumed that the Sun moved about the Earth; but with modern knowledge we know that the Sun is big enough to hold a million Earths, and we have this information without assuming whether it is the Earth or the Sun that moves. With this knowledge it is absolutely unreasonable to assume that the Sun moves about the Earth. This proof may be considered to

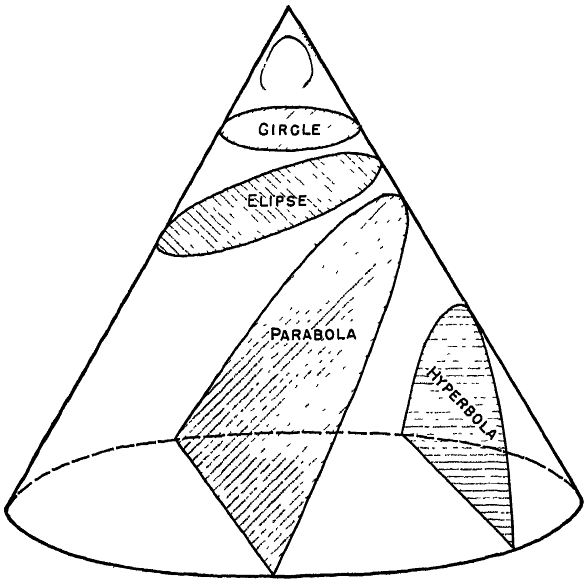


FIG. 53. The Conic Sections

date from Copernicus, in 1543, although Newton gave a more complete statement of it.

Orbits. A body moving about another in space must move in one of four different orbits. The first possible orbit is a *circle*, in which the body moves with uniform velocity and always at the same distance from the heavier body.

The second possible orbit is the *ellipse* with the heavier body at one focus. The ellipse may differ only slightly from the circle, as in the orbit of the Earth, or it may be a very flattened oval, as in the orbit of Halley's Comet, which is shown on page 354.

The third possible orbit is the *parabola*. It may be considered an ellipse stretched out until the distant end is open. A body mov-

ing about the Sun on a parabola would approach the Sun and leave the Sun in the same direction. While passing the Sun, a body moving in a parabola would move faster than a body moving in an ellipse.

The fourth possible orbit is the *hyperbola.* The hyperbola may be considered a parabola spread out. A body passing the Sun on a hyperbola would approach and leave in different directions, and while passing the Sun would move more rapidly than a body moving on a parabola.

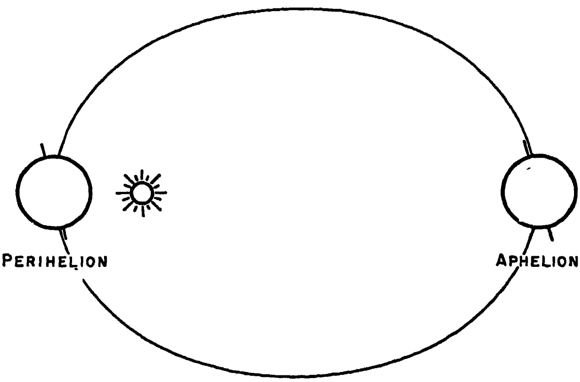


FIG. 54. Aphelion and Perihelion

All orbits possible under the law of gravitation can be obtained by cutting cones at various angles as shown in Fig. 53, hence the four possible curves are referred to as *conic sections,* or simply as *conics.*

The *orbit of the Earth* is an ellipse of small eccentricity, the variation in distance being only about 3 per cent. It is closest to the Sun about January 3, and most distant about July 4. The point in the orbit which is closest to the Sun is called *perihelion,* and the point in the orbit most distant from the Sun is called *aphelion* as illustrated in Fig. 54. The Earth moves in such a way that a line from the Earth to the Sun sweeps out equal areas in equal periods of time. This means that it moves most rapidly when closest to the Sun. (See Fig. 55.)

The *axis of the Earth is inclined 23½ degrees* away from the perpendicular to the plane of the Earth's orbit, or the Earth's equator

is inclined 23½ degrees to the ecliptic. As the Sun moves along the ecliptic, because of the Earth's motion in its orbit, its motion is most nearly parallel to the equator (least change in declination) about June 22 and December 22. The Sun's north and south motion (change in declination) is the most rapid near March 21 and September 23.

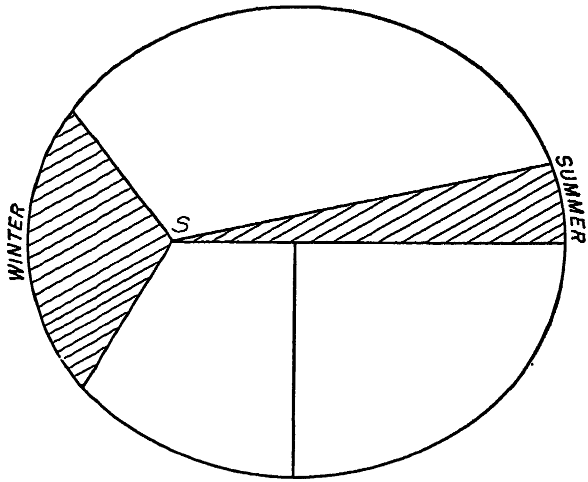


FIG. 55. The Law of Areas. The Earth moves more rapidly during Winter when nearer the Sun

Annual Variation in the Solar Day. The Earth revolves at an average speed of 18½ miles per second, or 66,000 miles per hour, and, as you have read, it sweeps around its orbit faster when closer to the Sun. This makes the solar day, defining day as the interval from noon to noon or from midnight to midnight, longer in Winter. The north and south motion of the Sun also affects the length of the day, defined in this way. The result is that the very longest day of the year usually is December 22. As this is the day for which the hours of daylight are the shortest, most people think of this as the shortest day.

The days about December 22 are about half a minute longer than 24 hours by our clocks and watches which keep mean, or average, time. Hence, at about this time, Sun noons are occurring later from day to day by about half a minute. To keep noon at

about 12:00 in spite of this, it is necessary to regulate our time so that noons are occurring about 15 minutes early in November and about 15 minutes late in February. The earliest noons occur about November 3, and the latest noons occur about February 12. This difference between apparent (or true) solar time and mean solar time is called the *Equation of Time,* and is tabulated in the *American Nautical Almanac.*

When noons occur early, sunrise and sunset must occur early also, as noon is the middle of the day. This effect, the early noons, tends to make sunsets earliest about November 3. The shortening of the hours of daylight tends to make the sunsets early also. This effect would make sunsets the earliest on December 22, when we have the shortest hours of daylight. The result is that the earliest sunsets occur about December 10 in latitude 40°.

The sunrises are affected in the same way by both the shifting of noon and the lengthening and the shortening of the day. From the shortening of the hours of daylight, the latest sunrises would occur about December 22 when the hours of daylight are the shortest. But from the shifting of noon the latest sunrises would occur about February 12 when noon comes the latest. The result of the two effects is to make sunrise the latest about January 8 in latitude 40°.

The Earth's Precessional Motion and Wandering of the Poles

Greek astronomers, as you have read, knew the Earth was round, and even measured its size. One of them accepted the rotation and revolution of the Earth. Another Greek astronomer, Hipparchus, announced that the equinoxes are moving westward slowly among the stars. The ecliptic, the plane of the Earth's orbit, remains fixed, but the plane of the equator is changing.

The Moon is not in the plane of the equator, and it pulls harder on the nearer side of the Earth's equatorial bulge than on the far side. This tends to throw the whirling Earth out of balance, and as a result the axis swings around like that of a wobbling top. The Sun also contributes to this effect, but its effect is much less than that of the Moon.

The Earth's Precessional Motion. The result of this "wobbling" is that the axis of the Earth marks out a circle about 47 degrees in

diameter as it swings around; but because of the relatively small size of the equatorial bulge, this motion is very slow. (See Fig. 56.) In the days of the Pyramids, Thuban or Alpha Draconis was the

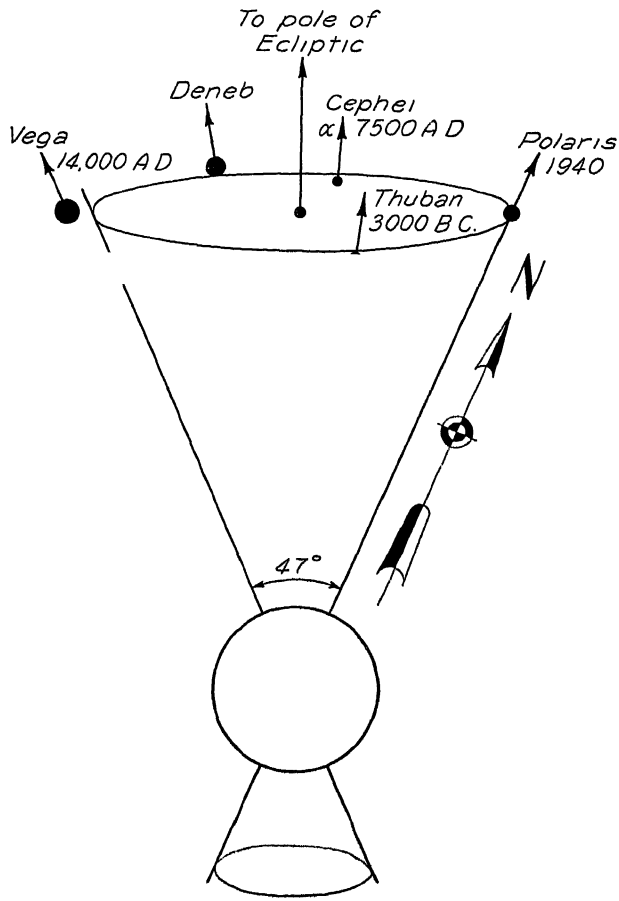


FIG. 56. The Change in the Celestial Pole as a Result of Precession of the Equinoxes

North Star. Polaris is the North Star now. Some 12,000 years from now, Vega will be the North Star. For the life-time of one person the position of the axis can be regarded as practically constant. If, however, observations are continued for several centuries, the

motion of the axis becomes appreciable. While a top may go all the way around in one or two seconds, the Earth requires 26,000 years for a complete circuit. This motion of the Earth's axis, or of the equinoxes, is called *precession.*

The movement of the Earth's axis, or westward motion of the equinoxes, causes a *change in the stars seen in a given season.* This amounts to a shift in the stars of a month, with respect to the seasons, in 2100 years, or of a day in 70 years. The change in a few centuries would not be noticed by primitive people, but the change in 2000 years would be quite noticeable. Let us suppose that at the time of the autumn equinox, when the Sun is rising due east and setting due west, certain stars are visible in the east just as the stars appear in the early evening. Two thousand years later, these same stars would be appearing in the early evening a month after the equinox when the Sun is setting many degrees south of due west.

This precessional shift means that 13,000 years from now, the stars we see on a summer evening will be seen on a winter evening.

Wandering of the Poles. In the precessional motion which we have just discussed, the Earth's axis describes a cone in space, but remains fixed in the Earth. It was found, in 1888, however, that the axis does move in the Earth itself.

The poles of the Earth wander about with an extreme variation of approximately forty feet from the mean position. There is an annual motion, due presumably to meteorological causes, and another motion with a period of about 430 days, which is assumed to be the natural period of vibration of the Earth. The result is, therefore, a very small change in the latitude and longitude of any particular station, which is inappreciable in navigation and with ordinary engineering instruments, but which must be taken into account in more refined geodetic work.

Exercises

1. Give and explain some proofs that the Earth rotates.
2. At what latitude does the Foucault pendulum (a) move through

an arc of 360° in 24 hours? (b) continue swinging without any rotation?

3. If you are at 60° north latitude, through what arc will the Foucault pendulum swing in one hour?
4. At what latitude does the Foucault pendulum rotate through 70° in 5 hours?
5. Calculate the speed of rotation of the Earth's surface at 30°, 60°, and 45° latitude.
6. What causes the speed of the Earth's rotation to lengthen and how is it detected? How much is it lengthening?
7. What is the difference in length between a sidereal and a solar day?
8. What are proofs that the Earth revolves? Distinguish between rotation and revolution.
9. How do aberration and parallax differ?
10. What are the conic sections? Why are they so called?
11. What are the possible orbits for celestial bodies?
12. What is the shape of the Earth's orbit?
13. Define aphelion and perihelion. When is the Earth at these points in its orbit?
14. Calculate the average speed in miles per second of the Earth's revolution in its orbit if the Earth is 93,000,000 miles from the Sun. How far does it travel in one day in its orbit?
15. Why does the length of the day vary within the year? When are the earliest and the latest Sun noons throughout the year?
16. When is the longest day of the year? Why is this so?
17. When do the earliest and the latest sunrises and sunsets occur?
18. What is the Earth's precessional motion, and what causes it? What change does it cause in the stars which we see from season to season in a few hundred years? In thousands of years?
19. What is the "wandering of the poles"? Do we notice it in navigational work? In geodetic triangulation?

☆ VI ☆

The Seasons and the Calendar

The Seasons

The Earth's axis is inclined to the plane of the Earth's orbit about the Sun at an angle of 66½°, instead of 90°. The axis is tipped 23½° away from the perpendicular, and *this tipping is responsible for*

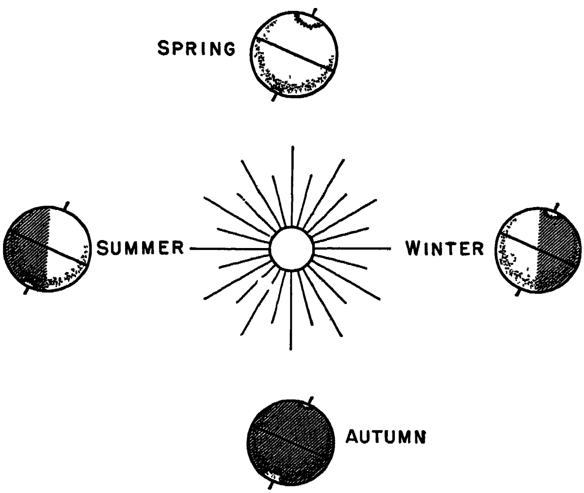


Fig. 57. The Cause of the Seasons

the climatic zones and the seasons. As the Earth goes around the Sun with the axis always pointing toward the north celestial pole (nearly toward Polaris), the rays of the Sun fall vertically at points from 23½° south of the equator to 23½° north of the equator. When the Sun is seen overhead north of the equator, all points in the Northern Hemisphere have more direct sunlight, and have more

hours of daylight than of darkness. When the Sun is seen overhead south of the equator, the Sun's rays are more inclined for points north of the equator, and there are more hours of darkness than of daylight. (See Fig. 57.)

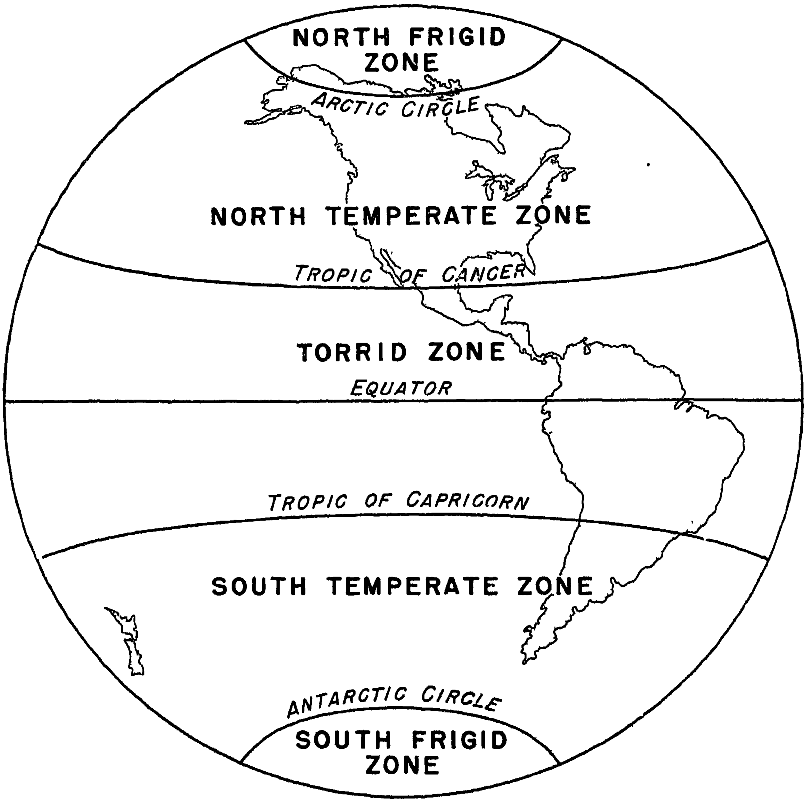


FIG. 58. The Climatic Zones

If the axis of the Earth were perpendicular to the plane of the Earth's orbit, the Sun would be seen overhead always at the Earth's equator, there would be no climatic zones and no seasons.

Climatic Zones. (See Fig. 58.) The *torrid* zone includes that part of the world between the Tropic of Cancer, 23½° north of the equator, and the Tropic of Capricorn, 23½° south of the equator. This is the land of the overhead Sun, for within this zone the Sun

passes through the zenith at least once each year (twice each year except quite close to the boundaries), and outside of this zone the Sun is never seen at the zenith. This is the hot zone.

The *north temperate* zone includes the region or belt between the Tropic of Cancer, 23½° north of the equator, and the Arctic Circle, 66½° north of the equator. The *south temperate* zone includes the region or belt between the Tropic of Capricorn, 23½° south of the equator, and the Antarctic Circle, 66½° south of the equator. The temperate zones include the region of the world where the Sun is never seen overhead, where it rises above the horizon for a short time at least on every day of the year, and where it never is above the horizon at midnight. The temperate zones include, in general, the regions of warm to cool climate.

The *north frigid* zone includes the area north of the Arctic Circle, that is, within 23½° of the North Pole. The *south frigid* zone includes the region south of the Antarctic Circle, that is, within 23½° of the South Pole. The frigid zones include the region where the Sun fails to rise above the horizon even at noon on at least one day of the year, and where the Sun is above the horizon at midnight for at least one day of the year. The frigid zones, because of this, are known as the "land of the midnight Sun." They are too cold, in general, for the human race to reach its greatest efficiency.

From a model showing the motion of the Earth about the Sun, it can be seen readily that there are *two reasons for Summer being warmer than Winter.* If a model is not available, Fig. 57 and Fig. 59 will show the effects fairly well.

The first and better known reason is that the rays of the Sun are *more direct during the Summer.* The Sun at a given hour of day is much higher in the sky in Summer than in Winter as is shown in Fig. 59. A given amount of sunlight in Summer covers much less area than at the same hour in Winter. In other words, a given amount of sunlight has less land, together with the air over it, to heat in Summer than in Winter.

The second reason is that the *Sun shines for a longer time in Summer* than in Winter. In early Summer, in latitude 40°, the Sun rises at about 4:30 a.m. and sets at about 7:30 p.m. It shines for about 15 hours out of the 24. In early Winter, in latitude 40°, the Sun rises at about 7:30 a.m. and sets at about 4:30 p.m. It shines for only about nine hours out of the 24.

Lag of the Seasons. The air over the Earth acts as a blanket, retaining the heat received from the Sun so that it is radiated off relatively slowly at night. In late June, for the Northern Hemisphere, the Sun is highest in the sky and shines for the longest time. For most of the United States, however, throughout July the heat received from the Sun by day is more than the heat radiated at night, and so the temperature continues to rise. In high inland

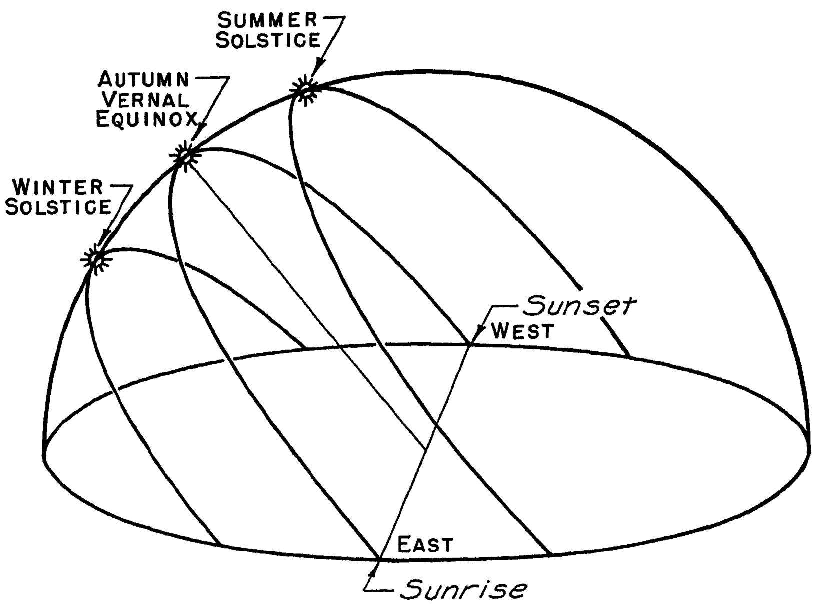


FIG. 59. The Limiting Diurnal Circles of the Sun, for Latitude 40° North

regions, as in some parts of our Southwest, the heat is radiated more rapidly and the hottest weather comes only 10 days after the solstice. For most of the interior, the hottest weather comes about 30 days after the solstice. Near the oceans, the warming up continues longer as heat is retained well by water. The greatest lag, about 100 days, occurs on parts of the coast of California.

Definition of the Seasons. A popular definition, and perhaps the first, of the seasons Summer and Winter is based merely on temperature. Summer is the warm period of the year, and Winter is the cold period of the year. This usage is common, even in popular

scientific works. As an example, one can read that the important difference between Summer and Winter in the North Central states, and Summer and Winter of northern Canada is not temperature, but length; that the hottest summer weather in northern Canada is not much cooler and the coldest winter weather not much colder than that of North Dakota or northern Minnesota, but the Summers are much shorter and the Winters are much longer in northern Canada.

Another popular definition is that Summer is the season of long days with the Sun high in the sky, and Winter is the season of short days with the Sun low in the sky. By this definition late June is spoken of as "midsummer," and late December is spoken of as "midwinter." The feast of St. John, June 24, is sometimes referred to as a midsummer festival by this usage. Because of the lag of the seasons, referred to in a previous paragraph, this definition does not agree with the first, but it appears occasionally in popular scientific articles and must be considered a correct usage in ordinary speech.

For scientific purposes, it is desirable to have a definition which is independent of the place and the calendar, but which agrees well with popular usage. Such a definition is provided by the fact that the year is divided into four nearly equal parts by the equinoxes and the solstices.

The three warmest months of the year, by our calendar, are June, July, and August for some places, and July, August, and September for others. The definition of Summer as the period from the summer solstice, about June 22, to the autumn equinox, about September 23, obviously is in good agreement with the temperature division for nearly all.

Scientifically speaking, therefore, Spring is the period from the vernal equinox to the summer solstice; Summer is the period from the summer solstice to the autumn equinox; Autumn is the period from the autumn equinox to the winter solstice, and Winter is the period from the winter solstice to the spring equinox.

The Northern and Southern Seasons. When the Southern Hemisphere is tipped toward the Sun, the Northern Hemisphere is tipped away from the Sun. It is obvious that the seasons in the two hemispheres are just reversed, that is, the season in the Southern Hemi-

sphere on any date is what the Northerm Hemisphere has on a date six months different, for practical purposes.

There is another difference between the northern and southern seasons. You have read earlier that the Earth is closest to the Sun about January 3 and farthest from the Sun about July 4. The fact that the Earth is closest to the Sun in the northern Winter and farthest from the Sun in the southern Winter tends to make the northern Winter more mild and the southern Winter more extreme. The same effect tends to make the southern Summer hotter and the northern Summer cooler, but this is less pronounced because another effect makes the southern Winter more severe. The South Pole is situated on a continent, high and mountainous land, while the North Pole is situated in an ocean. The southern Winter, therefore, is more extreme than the northern Winter for two reasons: the Earth is farther from the Sun, and the south polar regions are situated on high and mountainous land while the north polar regions are in an ocean.

The Calendar

Early people had no calendars, such as we use; they merely used the sky. As a marker for the month they used the Moon, and as a marker for the year they used the stars.

The first calendars on record used the lunar month which kept in step with the phases of the Moon, and began when the visible new Moon appeared low in the western sky in the early evening. The crescent new Moon was watched for just after sunset, so each new month began at that hour of day. It was natural, therefore, to consider the day also as beginning at that time, sunset.

There was no definite formula for keeping the month with the Moon, or the year with the seasons; they were kept correct by simple observation. If the sky could not be watched because of cloudy weather at the end of the month, a 30-day month was used. When the sky could be watched, the length of the month might be 30 days or 29 days, or after a period of cloudy weather perhaps only 28 days.

Marking the Year. With the day and the month beginning at sunset, it was natural to look for some marker seen at the same time which would decide on the beginning of the year. The most obvious

were the constellations, which change in position throughout the year.

The earliest use of a constellation to mark the year, as far as we have record, is the Babylonian use of the Gemini, *Castor and Pollux,* about 4000 B.C., when the visible crescent new Moon was seen beside Castor and Pollux at the time of the spring equinox. As the end of the year approached, the official would watch for the appearance of these stars beside the crescent Moon. If the weather was clear and the stars could be seen there, it was time for a new year. Using these stars made the year begin near the spring equinox.

The lunar month from new Moon to new Moon is about 29½ days. Twelve lunar months add up to 354 days and a fraction, or about ten days less than a solar year. It was, therefore, necessary to include an extra month about every three years to keep in step with the seasons. Apparently twelve months were used unless observation showed the thirteenth month was necessary.

The Jewish Calendar. The months of the Jewish calendar were also lunar, and it appears that they were kept in step with the Moon by the priests who watched the western sky immediately after sunset about the end of the month. If the crescent new Moon could be seen, the blowing of a trumpet announced the new month. If cloudy weather prevented watching, thirty days were used, as by other early people.

It is not known how the Jewish year in Biblical times was kept in step with the seasons. The orientation of their temple which faced the east, however, suggests that the priests used a simple, but reasonably exact rule. As the end of the twelfth month approached, they may have watched the rising sun morning after morning. If they judged it would be rising due east by the next full Moon, a new year was announced with the new Moon and the new month. If the rising Sun appeared too far south, a thirteenth month was inserted.

After some centuries' use of the lunar month and the solar year, it was natural that a rule would be developed for the insertion of the extra month to keep the year in step with the seasons. Such a rule is the *Metonic cycle,* which states that in a cycle of nineteen years, twelve shall be twelve-month years and seven shall be thirteen-month years. The rule also listed the twenty-nine- and thirty-

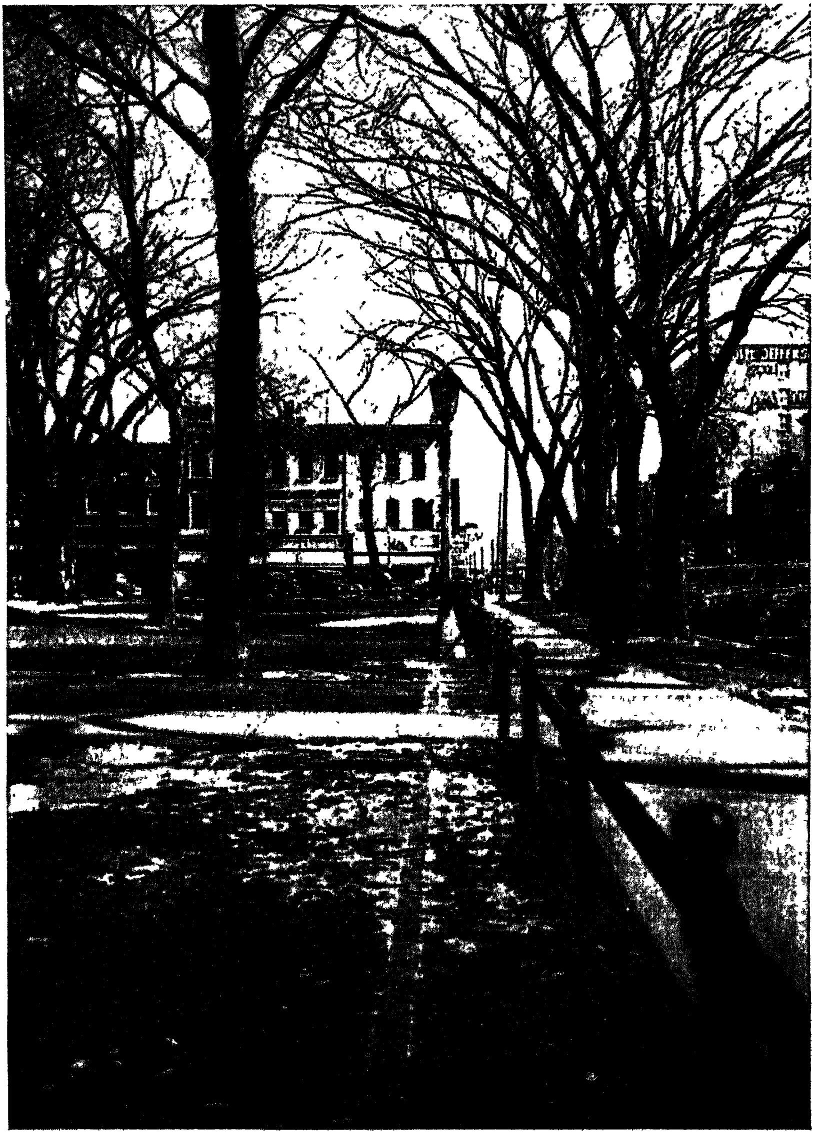


FIG. 60. Stationary East and West Shadow on Day of Equinox. Notice the line of unmelted snow

day months which should be used in each year to keep the months accurately in step with the Moon. The Metonic cycle is the basis of the calendar now used by the Jews in setting such religious festivals as Passover and the Jewish New Year. The present Jewish calendar uses tables proposed by Hillel II in 359 A.D. The Metonic cycle is used by Christians in setting the date of Easter and the associated religious festivals. The tables for Christian use were prepared under Pope Gregory XIII in 1582 A.D.

The Roman Calendar. The early Roman calendar is believed to have had ten named lunar months and an unnamed period of approximately 60 days in the winter. King Numa, who ruled from 715 to 672 B.C., introduced the months of January and February, making twelve months of variously 31 or 29 days totaling 355 days. This early Roman year began with March, so that the names of the months September, October, November, and December fitted the Latin numerals from which they were derived. That is, September was the seventh month, October, the eighth month, etc.

The Roman calendar was kept in agreement with the seasons by inserting an extra month of 22 or 23 days, called Mercedonius, every other year. In 153 B.C., for some unknown reason, the beginning of the Roman year was changed to January. At that time, the introduction of the extra month, Mercedonius, had become political. The Pontiffs were not following the rule for keeping the year with the seasons; so that when Julius Caesar came into power, he found the months about 90 days (or three months) off the traditional seasons. Caesar decided, and rightly, that the calendar should be taken out of politics and made consistent by adding extra days to certain months, making the lengths what we have now, and making the year 365 days in common years, and 366 days in leap years.

The Roman months Quintilis and Sextilis were named July and August after the Roman emperors, Julius Caesar and Augustus Caesar.

The Rule for Easter. According to the Jewish calendar, Passover began on the evening of the 14th day of the first month of the Jewish sacred year. For practical purposes, this was the first full Moon of Spring. The crucifixion occurred on Passover Eve, and the resurrection occurred on the Sunday following. Hence, according to the

calendar in use in Palestine in the time of Christ, the resurrection occurred on the Sunday following the first full Moon of Spring.

The festival of Easter is supposed to commemorate the resurrection, and the church fathers preferred to follow the old calendar in setting the anniversary. At the Council of Nice in 325 A.D., they assumed that Spring began on March 21, and the following rule was adopted: Easter shall be celebrated on the Sunday following the first full Moon on or after March 21.

The calendar of Julius Caesar, called the Julian calendar, inserts an extra day every four years, making the average length of the calendar year 365¼ (365.25) days. The true length is 365.2422 days, which is shorter by 0.0078 days in one year, or by 3 days in 400 years. In the 16th century, spring began about March 11, instead of March 21. Therefore, in 1582, Pope Gregory XIII ordered that ten days be dropped from the calendar, to make the old church rule correct.

Rule for Leap Year. To keep the calendar year correct Pope Gregory decreed a new rule for leap year, which eliminated the error of three days in 400 years. This rule is:

Years divisible by four are to be leap years unless they are also divisible by 100, in which case they are to be leap years only if divisible by 400. Translating this rule into figures, the length of the Gregorian calendar year is

$$365 + 1/4 - 1/100 + 1/400.$$

Writing as decimals:

$$365 + 0.25 - 0.01 + 0.0025.$$

Combining, we obtain 365.2425 days for the Gregorian calendar year. The true length is 365.2422 days, so the error in one year is 0.0003 day, or in 10,000 years the error will be 3 days.

To apply this rule, let us consider the years 1900, 1938, 1940, and 2000. The number 1900 is divisible by 4, which would make it a leap year, but it is divisible by 100, which takes it out, and it is not divisible by 400. That year was not a leap year. The number 1938 is not divisible by 4, so it was not a leap year. The number 1940 is divisible by 4, and not divisible by 100, so 1940 was a leap year. The number 2000 is divisible by 4, by 100, and by 400. The year 2000 will be a leap year also.

How Leap Year Operates. To show how the extra day added in leap year operates, let us take the years 1940 to 1944, and use the length of the year as 365.25 days, the approximate, instead of the exact, length. In 1940, the spring equinox occurs March 20 approximately at twelve noon, central standard time. In 1941, the extra quarter of a day throws the equinox forward to March 20, six p.m. In 1942, the equinox moves up another quarter of a day to March 20, twelve p.m. (midnight). In 1943, the equinox moves up still another quarter of a day to March 21, six a.m. In 1944, the equinox moves up still another quarter of a day. This would be March 21, twelve noon, but 1944 is a leap year, and the addition of the extra day to February throws the date of the equinox back to March 20, twelve noon. This puts the time of the equinox within a few minutes of that four years earlier, in 1940.

The reform of Pope Gregory was adopted immediately in all Roman Catholic countries. Some Protestant countries, such as England and her colonies, did not make the change until 1752, and Greek Catholic countries, as Russia, did not make the change until 1918.

Calendar Reform. The Gregorian calendar does a very good job of indicating the seasons by the month and day of the month, but there are objections, chiefly to the changing relation between the week and the year. The year is 52 weeks plus one day (two days in leap year) in length. Because of this, if one year begins on Sunday, the next begins on Monday (Tuesday if the preceding year is a leap year). The chief objections raised to our calendar are the following:

1. The months are unequal in length, varying from 28 to 31 days.
2. The number of working days varies from month to month.
3. If the year is divided into quarters or half years by months, the periods are not equal.
4. There is a variation from year to year of the number of working days and the position of holidays in the same month.
5. Each year there must be new calendars or schedules for business, sport, school, religion, court, etc.
6. The new schedules each year result in many conflicts of dates.
7. The extra day in leap year should be added at the end of the year rather than to February in the early part of the year.

Favored Proposals for Reform. One plan, called the *twelve-month equal-quarters plan*, would divide the year into four equal quarters of three months, thirteen weeks, or (except for the extra day) 91 days each. The three months would be 31, 30, and 30 days. That is, January would be 31, February 30, and March 30; and the succession would be repeated by each three months throughout the year. The first month in each quarter would have five Sundays and the number of working days in each month would be twenty-six. The 365th day would be taken care of by an eight-day week, including the extra day (two extra days in leap year) as a "blank" day.[1]

Another plan, which has received considerable attention by some, is the *thirteen-month calendar*. This calendar would divide the year into thirteen equal months of twenty-eight days, or four weeks each, with month-ends always falling on a week-end. The 365th day (two extra days in leap year) may be taken care of in the same way as in the above plan, by including it as a "blank" day in one eight-day week.[2]

EXERCISES

1. Explain how the tipping of the Earth's axis causes the seasons.
2. What fixes the width of the climatic zones?
3. What would be the width in degrees of the corresponding zones on Jupiter and Saturn if the planes of their equators are tipped to their orbits 3° 7′ and 26° 45′ respectively?
4. Why is it warmer in the Summer than in the Winter?
5. What is meant by "lag of the seasons"? Why is it different in different regions?
6. Why are Winters in the Northern Hemisphere milder than those in the Southern Hemisphere?
7. How did early people determine the beginning of a new year?
8. What is the Metonic cycle? For what is it in use today?

[1] A calendar of this type is sponsored by the World Calendar Association of New York City.

[2] The thirteen-month calendar is supported by the International Fixed Calendar League, Rochester, New York, and was advocated actively by the late George Eastman.

9. What changes did Julius Caesar make in the Roman calendar?
10. When and by whom was the present rule for Easter set?
11. What is the present rule for leap year? When and by whom was it devised?
12. Calculate the error of the present calendar in the period from its first adoption in Catholic countries to the year 1950.
13. Give what you consider the four most important objections to our present calendar.
14. Give two proposals for calendar reform.

☆ VII ☆

The Weather

Weather forecasting was probably practiced by earliest man, and references to the weather exist in the earliest writings. The first known systematic discussion of weather was the *Meteorologica* of Aristotle. A pupil of Aristotle wrote on winds and weather signs. Then, for two thousand years, there is no recorded advance in the knowledge of weather. The treatment of meteorology as an exact science began with the invention of the thermometer by Galileo in 1607.

The first weather charts were prepared by the French astronomer Laplace, the German astronomer Brandes, and others during the period 1800-1820. International cooperation began in 1853, and a British meteorological office was established in 1854.

The United States Weather Bureau began in 1870 as a part of the Signal Service under the direction of the War Department. The Weather Bureau continued under the direction of the Army until 1891 when it was placed under the Department of Agriculture. It continued under the direction of the Department of Agriculture until 1940 when it was transferred to the Department of Commerce by an Act of Congress. The work of the U. S. Weather Bureau is divided into such subdivisions as climatological, hydrological, river and flood, marine, and aeronautical meteorology. These will be discussed more fully in a later chapter.

Weather forecasts for industrial or agricultural purposes may usually be stated in rather general terms and if conditions vary somewhat from the prediction, no harm is done. The aviation forecaster, however, cannot make serious mistakes in his forecasts without the possibility of tragic results. He is interested primarily in conditions in the atmosphere above the Earth's surface, so he must

make a three-dimensional, instead of the former two-dimensional study, of the weather changes.

Collection of Weather Data. Weather data are gathered from stations distributed throughout this country, and from other nations and ships at sea. The distribution of stations in the United States is most dense along the established air routes. Observations at air-

FIG. 61. Cumulus Clouds changing to Cumulonimbus. Photograph from U. S. Weather Bureau

ways stations are made hourly and such stations as are equipped with radio broadcast facilities make half-hourly observations in addition.

The weather stations at air terminals are operated by Weather Bureau personnel. Most of the large airlines maintain their own weather staffs which are used to supplement for their own particular needs the official data prepared by the U. S. Weather Bureau.

Observations. There are two general classes of observations, sur-

face observations and upper air observations. The surface observations include visual and instrumental ones. Visual work includes observations of clouds (types and amount), the state of the weather, and the visibility. Instrumental observations include measures of pressure, temperature, humidity (dew point), winds, both as to direction and velocity, ceiling, and precipitation. These are known as the meteorological elements.

Clouds. Clouds are composed either of droplets of water averaging about one-thousandth inch in diameter, or in the case of cirrus or other high clouds, of ice crystals. The actual weight of visible water in the cloud may vary from about 1.5 to 8 grams per cubic foot. The following table gives the more important clouds, together with their average heights:

TABLE VI

Name of Cloud	*Height*
Fog (not strictly a cloud)	0 miles
Nimbus	¼ "
Stratus	¼ "
Cumulus (bottom of towering type)	½ "
Cumulus (top of towering type)	2 "
Altostratus	3½ "
Cirrocumulus	5 "
Cirrus	7 "

These clouds will be discussed more fully in the next chapter.

It is important for an airplane pilot to know the extent to which the sky is covered. There are four general types of sky: *clear,* where total sky cover is less than one-tenth; *scattered,* when one-tenth to five-tenths is covered by clouds; *broken,* when more than five-tenths, but not more than nine-tenths, of the sky is covered; *overcast,* when more than nine-tenths of the sky is covered.

State of Weather. This is a mere statement by the weather observer of his visual observations. His notes include, for example, whether rain, snow, hail, and thunderstorms are active or imminent, and he passes this information on to any pilot in his territory.

Visibility. It is extremely important to a pilot to know how far he will be able to see during take-off, during the flight, and in landing at his terminal.

Visibility is the mean *greatest distance* toward the horizon that *prominent objects,* such as mountains, buildings, towers, etc., *can be seen* and identified by the normal eye. Visibility at night is measured by the distances at which lights of certain specified candlepower can be seen; it is usually reported in miles.

FIG. 62. Towering Cumulus Clouds seen from above. Photograph from U. S. Weather Bureau

Pressure. The pressure of the atmosphere is obtained with a barometer, which may be either of the mercury or aneroid type.

The essential feature of an aneroid barometer is a metallic box or cell, partially exhausted of air. As the pressure of the air changes, the upper, or free, surface of the cell contracts or expands, and this movement operates the hand, or pointer, of the barometer.

A continuous record of the pressure is given by a *barograph,* on which a recording cylinder is driven by a clock, geared to give a 7-day record in one revolution.

Since the barometer measures the weight of the air above a given station it is clear that, if the barometer were carried aloft in an airplane, the pressure recorded on the barometer would be less.

When a simple aneroid barometer is calibrated in terms of altitude it is called an *altimeter.*

For every inch of mercury decrease in pressure up to a height of about a mile, the elevation increases approximately 1,000 feet. At a height of three or four miles the air is lighter, and consequently the drop in mercury is less. The actual pressure at the station is called the station pressure. In the United States *pressures are reduced to sea level* and to the *5,000-foot level.* Most weather maps use sea level isobars.

The following *pressure extremes* are of interest. The lowest sea level pressure ever observed in the United States has been 26.35 inches and in the World, 26.16 inches. The highest sea level pressure ever observed in the United States has been 31.5 inches and in the World, 31.7 inches.

Temperature. The temperatures that are considered in meteorology are those of the free air. There are several types of thermometers used to measure and record temperature, as follows: the ordinary *mercurial* thermometer; the *sling* thermometer which may be whirled rapidly to obtain free air temperature; and a *maximum* thermometer which has a constriction near the base that allows the mercury to rise. When temperature falls the mercury column in a maximum breaks leaving the temperature indication at its maximum value. Two other types are the *minimum* thermometer—an alcohol thermometer that has a small glass index which is pulled down by the upper surface of the alcohol, but which allows the alcohol to flow by it as the alcohol expands with increasing temperature, leaving the index at the minimum temperature—and the *thermograph,* a recording instrument which shows a graph of the temperature on a revolving drum.

The hours at which observations of temperature are made must be properly distributed throughout the day if we wish to obtain the true mean daily temperature corresponding to the average of twenty-four hourly observations. If the mean is derived from observations made mostly during the daytime, as is still sometimes the case, the resulting mean is too high, because the temperatures of the cooler portion of the twenty-four hours do not enter sufficiently into the result.

It has been shown that the northward distribution of animals

and plants of warmer zones is controlled by the total quantity of heat, that is, the sum of the daily mean temperatures above 42.8°F, while the southward distribution of the northern species is determined by the mean temperature of the hottest part of the year. The latter is expressed, in a general way, by the mean temperature of the six hottest weeks of the year.

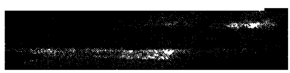


FIG. 63. Cumulonimbus Cloud with Anvil. Photograph from U. S. Weather Bureau

It has been found that the mean annual temperatures from city readings, even when the thermometers are properly exposed, are from one-half to one degree higher than for the surrounding country. The difference is most marked for minimum temperatures in cold waves. In one Winter, the minimum temperatures recorded in the large cities were, on different days, 2°.8, 4°.4, 7°.2, 10°.6, and 15° higher than those recorded at surrounding Weather Bureau stations.

Humidity. Humidity is a measure of the amount of invisible, or gaseous, water vapor in the atmosphere. There is an upper limit to the amount of water vapor which can be contained in a given

space at a given temperature. When this maximum limit is reached, the space is said to be saturated. If the temperature falls after the air is saturated, some of the invisible water vapor will condense out in the form of cloud or dew.

Humidity may be measured by a *psychrometer* or a *hygrometer*. The *psychrometer* is made of two thermometers, one of which has a gauze bag over the bulb. The gauze is kept wet with water and air is passed rapidly past both thermometers. Evaporation of water from the gauze causes the temperature of the wetted thermometer to fall. The lowest temperature reached is called the wet-bulb temperature. This is compared with the reading on the dry thermometer, called the dry-bulb temperature, to determine how much moisture is in the air. When the air is saturated, the wet-bulb temperature is equal to the dry-bulb temperature. The *hygrometer* is actuated by the expansion and contraction of a strand of human hair which changes its length when changes in water vapor content occur. The variation of length may be transmitted onto a dial mechanism or onto a recording drum as in the hygrograph.

The *relative humidity* is the ratio of the moisture content of the air to the moisture content of saturated air at the same temperature. It is 100 per cent for saturated air and 0 per cent for perfectly dry air.

A person's comfort depends upon the wet bulb reading as well as on the dry bulb, or usual, temperature reading. In the hot regions of the southwestern United States, the relative humidity is so low that the wet bulb reading may be lower than in the eastern states, where the dry bulb reading is much lower. In Winter, homes and offices without humidifying equipment become exceedingly dry. Consequently, even though people are dressed more warmly than in Summer, the temperature must be kept higher for comfort. People who are quite comfortable at 65°-70° when the building is unheated, may need 75° for comfort when it is heated.

The temperature to which the air must be cooled at constant pressure in order that it shall become completely saturated is the *dew point*. Any further cooling will condense out some of the moisture. If a glass of ice water collects moisture on the outside, its temperature is below the dew point temperature of the surrounding air.

Moisture laden air is lighter than dry air at the same temperature, in spite of the common feeling that air with a high humidity is heavy. Consequently, it tends to rise, especially if it is also warm. As it rises, it expands and cools, and if the temperature drops below the dew point clouds are formed. The droplets in a cloud are exceedingly small, but if they increase in size because of collisions and condensation, *precipitation* may occur.

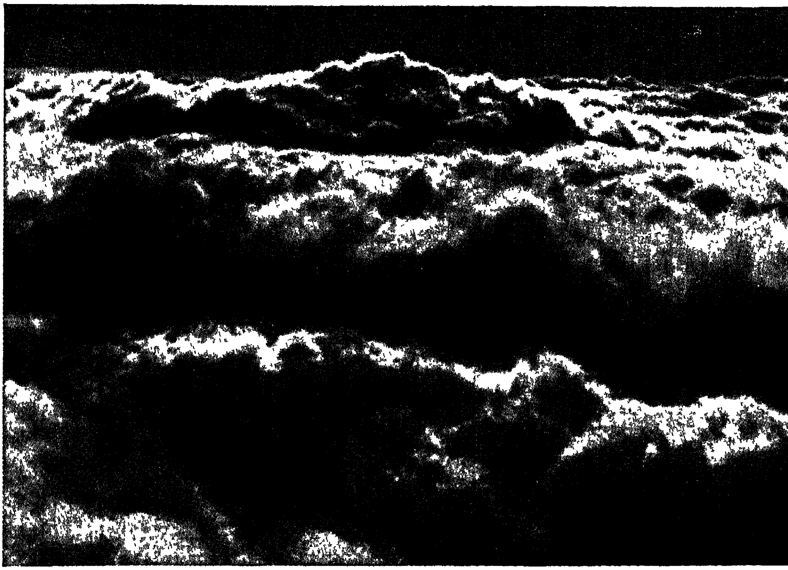


FIG. 64. Stratocumulus Clouds seen from above. Photograph from U. S. Weather Bureau

Precipitation in the form of uniform minute (in diameter less than one-fiftieth inch) and very numerous drops, which seem almost to float in the air, is called *drizzle*. It was designated in the past as "mist." *Freezing* drizzle is the same as "drizzle," except droplets instantly freeze to objects in the open which they strike, forming glaze or frost.

Rain consists of falling drops of water which are larger than the drops in drizzle; that is, the diameter of most drops is greater than one-fiftieth inch. They fall in still air faster than 10 feet per second. *Freezing* rain is rain which instantly freezes to objects in the open,

generally forming glaze. This should not be confused with sleet (ice pellets). *Sleet* is transparent, globular hard grains of ice, ranging from one twenty-fifth to four twenty-fifths inch in size; it rebounds when falling on hard surfaces and is formed by the freezing of rain drops.

Snow consists of falling white or translucent ice crystals, mainly in branched hexagonal shapes ("stars"), often mixed with simple ice crystals. *Snow pellets* are white, opaque, round, or rarely conical, grains, of snowlike structure, one-sixteenth to one-quarter inch in diameter. They are crisp and easily compressible, rebound and often burst when falling on hard ground. They occur almost exclusively in showers.

Ice balls or stones, with diameters ranging from one-fifth inch to two inches or more, which fall either detached, or fused in irregular lumps are *hail.* They are either quite transparent or composed of alternating clear and opaque, snowlike layers, the clear layers being at least one twenty-fifth inch thick. Hail occurs almost exclusively in violent or prolonged thunderstorms, and never at temperatures below freezing. Hail is extremely dangerous to aircraft. *Small hail* is made up of semitransparent, round or conical grains of frozen water, generally consisting of a grain of soft hail as nucleus, with a very thin ice layer around it, which gives a glazed appearance. Small hail is not easily compressed or crisp, and even when falling on hard ground does not generally rebound or burst. It is wet, because it usually falls at temperatures above freezing.

Winds. The Sun's rays shining on the Earth warm the air. The warming is different in different places, because of the difference in the inclination of the Sun's rays and because of the difference in the hours of sunlight. In addition, clouds may shut off the Sun's rays and prevent the warming of the lower air. Warm air is less dense than cool air, and moist air is less dense than dry air. Both tend to rise. The variation in density produces a variation in barometric pressure, and the winds are nature's method of readjusting the pressure. Wind is air in motion.

The *direction* of a wind is the direction from which it is blowing, that is, a west wind is a wind blowing from the west. The direction is determined by a wind vane.

The *velocity* can be obtained with an *anemometer*, which measures the velocity by the rate of rotation of metal cups, or it can

be estimated from the effect of the wind on various objects. Surface winds at airdromes are indicated by wind socks, wind vanes, anemometers, wind tees, and smoke boxes. Away from the airdrome some of the various things that indicate the surface wind are smoke columns, water waves, dust, windmills, clothes on clotheslines, movement of grass, brush, and trees.

The Beaufort Scale for winds was introduced by Admiral Beaufort in 1806. The following table gives the numbers, names, velocities, and effects according to this scale.

TABLE VII. BEAUFORT SCALE OF WINDS

Number[1]	*Name*[2]	*Miles per Hour*	*Effects*
0, 1, 2	Light wind	0–7	Varies from calm with smoke rising vertically, to a rustling of the leaves, and the moving of an ordinary wind vane.
	Gentle wind	8–12	Leaves and small twigs in constant motion; wind extends light flag.
	Moderate wind	13–18	Raises dust and loose paper; small branches are moved.
	Fresh wind	19–24	Small trees in leaf begin to sway; crested wavelets form on inland waters.
6, 7	Strong wind	25–38	Large branches and whole trees in motion; whistling of telephone wires; umbrellas used with difficulty.
8, 9	Gale	39–54	Breaks twigs off trees; some damage to roofs.
10, 11	Whole gale	55–75	Seldom experienced inland; trees uprooted, considerable damage to buildings.
12	Hurricane	Over 75	More or less complete destruction.

Upper wind velocities are obtained by following the ascent of a hydrogen-filled balloon with a *theodolite*, or angle measuring, in-

[1] This is the Beaufort number, which is used in the weather observer's report of the wind velocity in aeronautical work.

[2] These are terms used in U. S. Weather Bureau forecasts.

strument. When clouds or dust interfere, balloons with automatic radio transmitters attached may be used. A directional receiver on the ground may follow these instruments in any kind of weather except severe thunderstorms.

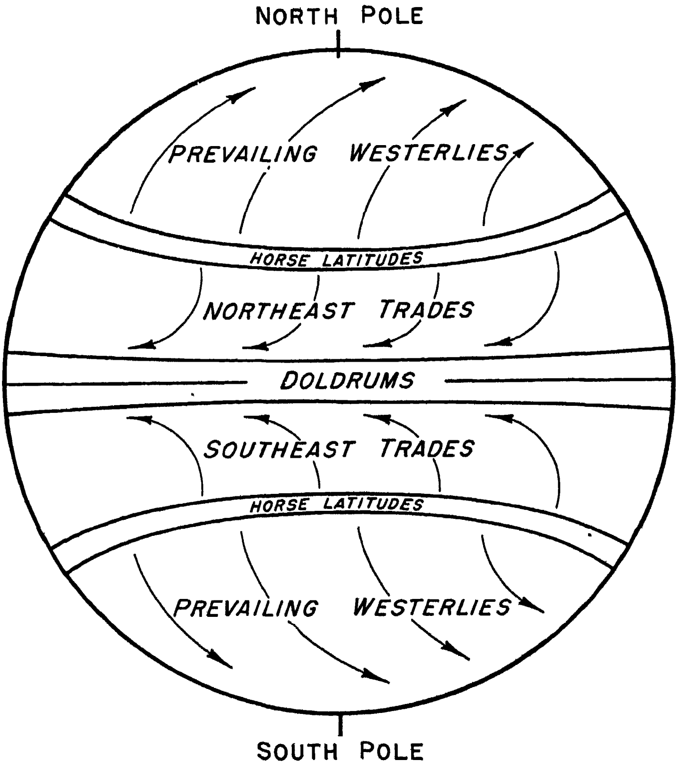


FIG. 65. The Surface Winds of the Earth

The maximum effect of solar radiation is felt in the tropics. Much more heat is received by the atmosphere near the equator than at the poles. When air is heated it expands so that a cubic foot of air at the equator will weigh less than the same volume of air at the poles. Hence, the air rises at the equator, moves aloft toward the poles, and returns along the surface toward the equator, resulting in a general circulation.

As explained on page 108, the Earth's rotation deflects northward

moving air to the east in the Northern Hemisphere, and to the west in the Southern Hemisphere. This effect produces the well-known *trade winds* at the surface—which form a great westward moving current near the equator—and the antitrades aloft. At about latitudes 30° N and S the antitrades appear as eastward moving currents at the ground. The westerly winds on the poleward side of these antitrades form the *prevailing westerlies* of the middle latitudes. In the United States the wind on the average increases in velocity up to the bottom of the stratosphere. More than 85 per cent of the time the wind is from a westerly quarter at elevations above 10,000 feet; but this "westerly" may be anything from northwest to southwest. (See Fig. 65.)

Cyclonic Storms. In the United States, the weather changes are dependant primarily on those great whirling storms, or *extra-tropical cyclones*, which move slowly across the country, in a general way from west to east. Milham's description will be used with some modifications.

The storms are usually oval in form, the ratio of the two axes being nearly two to one, and the direction of the longer axis is northeast-southwest. The winds blow spirally inward towards the center, turning counter-clockwise in the Northern Hemisphere and clockwise in the Southern as shown in Fig. 66. The wind velocity is usually moderate, and only in rare cases enough to be destructive. It is least on the outside and near the center, and greatest in between.

There is a marked rise of temperature on the south and east side of the storm, where the winds blow from some southerly quarter, and a decided drop in temperature on the west side, where the windows blow from some northerly quarter. On the southern and eastern sides of the storm, the absolute humidity increases so fast that even the relative humidity sometimes increases in spite of the increased capacity of the air for moisture as a result of its higher temperature. In the central part of the storm, both the absolute and relative humidity are high. On the west side, the absolute humidity is very small, where the winds are from the north and the temperature is low, but the relative humidity remains high because of the small capacity of the air for water vapor.

The cirrus clouds are almost entirely lacking on the west side, but extend far out to the east. The nimbus cloud area, which also

marks the region of precipitation, is not concentric with the isobars, but is located chiefly in the southeast quadrant. There are two series

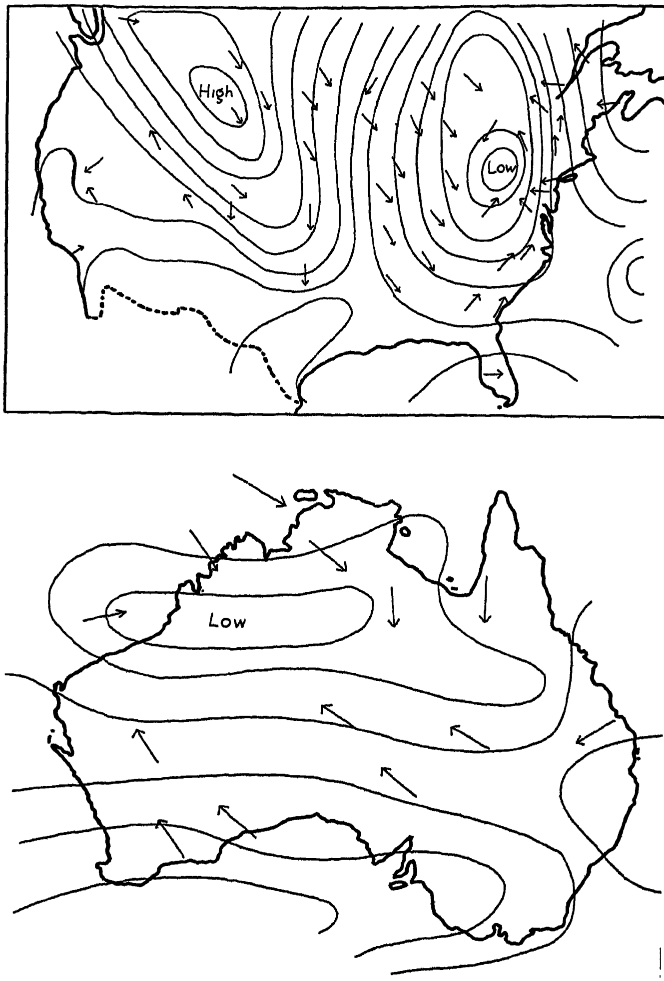


FIG. 66. Rotation of Cyclonic Storms in Northern and Southern Hemispheres. (Drawing from University of Chicago Press)

of transition clouds from the cirrus to the nimbus. The cirrus may become heavier, becoming first cirrostratus, next altostratus, then

stratus or fractostratus, and finally nimbus. The cirrus may also become cirrocumulus, then altocumulus, next stratocumulus, and finally nimbus. Sometimes both forms of transition may be seen in different parts of the sky at the same time.

On the west side of the storm, the transition from nimbus to clear sky is usually this: the nimbus becomes fractonimbus, disclosing often an upper cloud area of cirrus or cirrocumulus. The upper cloud area extends but a short distance from the center, and then ceases. The fractonimbus usually becomes stratocumulus, then fractocumulus, and finally cumulus, or a clear sky.

The diameter of the storm formation averages about 1200 miles and varies all the way from a few hundred miles to several thousand.

Tropical cyclonic storms, in contrast to extratropical cyclones, do not occur frequently. On the average fewer than six tropical cyclones are reported in North American waters annually. They form only over certain well defined and limited water areas of the tropics and quickly lose energy on reaching a large land surface. They also lose energy, although more slowly, as they progress toward middle latitudes over the oceans, usually at the same time expanding in size. On nearing or reaching the higher latitudes of the ocean they either dissipate or take on the characteristics of an extratropical storm.

Tropical cyclones are confined almost entirely to five fairly definite regions, three in the Northern Hemisphere and two in the Southern. These regions are the West Indies, Gulf of Mexico, and coast of Florida; the China Sea, Philippine Islands, and Japan; the Arabian Sea and Bay of Bengal; the waters to the east of Madagascar and Mauritius; the waters to the east of Australia and Samoa.

Tropical cyclones originate in the region known as the *doldrums,* that narrow belt lying between the northeast and southeast trade winds. It is a region characterized by thunderstorms and squalls. The south Atlantic Ocean is free from cyclones of tropical origin, the reason being that the Atlantic doldrums are almost entirely north of the equator, their southernmost position, which occurs in March, being commonly between latitude 3° N and the equator. They rarely reach south of that latitude and, if so, only for a brief period. If they reach the Southern Hemisphere, the winds will blow in a clockwise direction about the center of the cyclone. The usual track of the tropical cyclone resembles a parabola, of which the

first branch has its extremity in the region of the doldrums, and the second branch, running to the east and north, has its extremity in middle latitudes. Here it either dissipates or takes on the form of an extratropical cyclone.

Fully developed, the tropical cyclone consists of a well-defined area, more or less circular in shape, throughout which the atmospheric pressure diminishes rapidly on all sides toward the center, or point of lowest barometer. Within this area of barometric depression the winds blow with great force. At the center itself is a region seldom more than 10 or 20 miles in diameter throughout which calm air prevails. Here, too, the dense canopy of cloud which overhangs the storm area is pierced, forming the so-called "eye of the storm." The seas within this area are, however, violent and confused, sweeping in from all sides with overwhelming violence. Gale winds, high seas, and torrents of rain usually accompany these tropical cyclones.

The size of tropical cyclones varies greatly. In the case of West Indian hurricanes, the average diameter is some 300 miles. The diameter of the area of destructive winds is, however, much smaller. The size of the vortex, or calm area, rarely exceeds 15 to 20 miles in diameter and may be as little as 7 miles.

Tropical cyclones are almost invariably preceded by a day of unusual clearness, when distant objects not ordinarily visible stand out with great distinctness. The atmosphere at such times is more than usually oppressive. There is frequently an unsteady barometer, sometimes a little higher than usual. The barometer is by no means an infallible guide, but after the beginning of a storm it will more or less accurately indicate the rapidity of approach and the distance from the center. Frequently a swell from the direction of the storm sets in before any other indication becomes marked. Such a swell has in some instances given warning of a tropical cyclone days in advance of its arrival.

As the cyclone comes nearer, the sky becomes overcast with a delicate cirrus haze, which becomes gradually more and more dense until the dark mass of the true hurricane cloud appears upon the horizon. Rain forms one of the most prominent features of the storm. In the outer portions it is fine and mistlike, with occasional showers, these later increasing in frequency and in copiousness. In the

neighborhood of the center, rain falls in torrents. The rain area extends farther in advance of the storm than in the rear.

It is very important to determine as early as possible the *location* and *direction of travel* of the center. While this cannot be done with absolute accuracy, a sufficiently close approximation can be arrived at so that the ship can maneuver to good advantage.

FIG. 67. Crepuscular Rays, or the "Sun Drawing Water." Photograph by F. W. Kent

Under average conditions, in the Northern Hemisphere, stand with the face to the wind; the center of the cyclone will bear approximately 110° to the observer's right. In the Southern Hemisphere, stand with face to the wind; the center of the cyclone will bear approximately 110° to the observer's left.

Another type of cyclonic storm is the *tornado*. It is a very violent whirling storm of small diameter accompanied by heavy rain, usually by lightning, and frequently by hail. Tornadoes are distinguished from hurricanes and tropical cyclones by their small size and duration. They are usually only a few hundred yards in diameter and their track on the ground is usually less than 25 miles in length. In the United States, they occur most frequently in the

central portion of the Middle West, but they have been reported from every state in the Union. Forecasting their occurrence is so difficult that most forecasters refrain from the practice.

Most of the tornadoes in the United States occur in the *late Spring* and *early Summer* with a secondary maximum in the Fall. There is a very close relation between tornadoes and thunderstorms. The thunderstorm will be discussed later. Tornadoes build down from above, strike the surface at one point, then sometimes skip some distance before reaching the surface again. They move with the prevailing wind. Strong winds aloft, with light surface winds, will cause the upper portion of a tornado to be carried ahead and may lift the tornado from the ground or destroy it completely. Winds aloft of about the same velocity as those near the ground will cause tornadoes of longest duration and intensity.

Wind in a tornado vortex may exceed 500 miles per hour and the centrifugal force in a tornado causes a large reduction of pressure in the center of the whirl. Houses in the path of a tornado may seem to explode. Dust and debris are picked up by the suction effect giving the tornado the appearance of a black sinuous cone extending from the ground up to the base of the clouds. The appearance is so typical and the extent so small that in daytime the path may be avoided without difficulty. Since, like thunderstorms, they move with the prevailing winds, the path of an observed tornado may be forecast roughly. A pilot should find it easy to avoid a tornado except possibly at night, and even then the accompanying lightning should give him a good clue to its location.

Ceiling. The ceiling is the height in feet of the lowest level below 10,000 feet at which the cloudiness covers more than one-half of the sky. If precipitation or fog prevents the observer from seeing any clouds, the ceiling is zero.

To determine the height of the ceiling at night, ceiling-light projectors, a form of electric searchlight, are employed to throw a spot of light on the under side of the cloud layer. The projector throwing a vertical beam is located at a horizontal distance of 500 to 1,000 feet or more from the point of observation of the light spot. Knowing this fixed distance, it is only necessary to measure the angular elevation of the spot of light from the observing point to compute the height of the light spot or the ceiling.

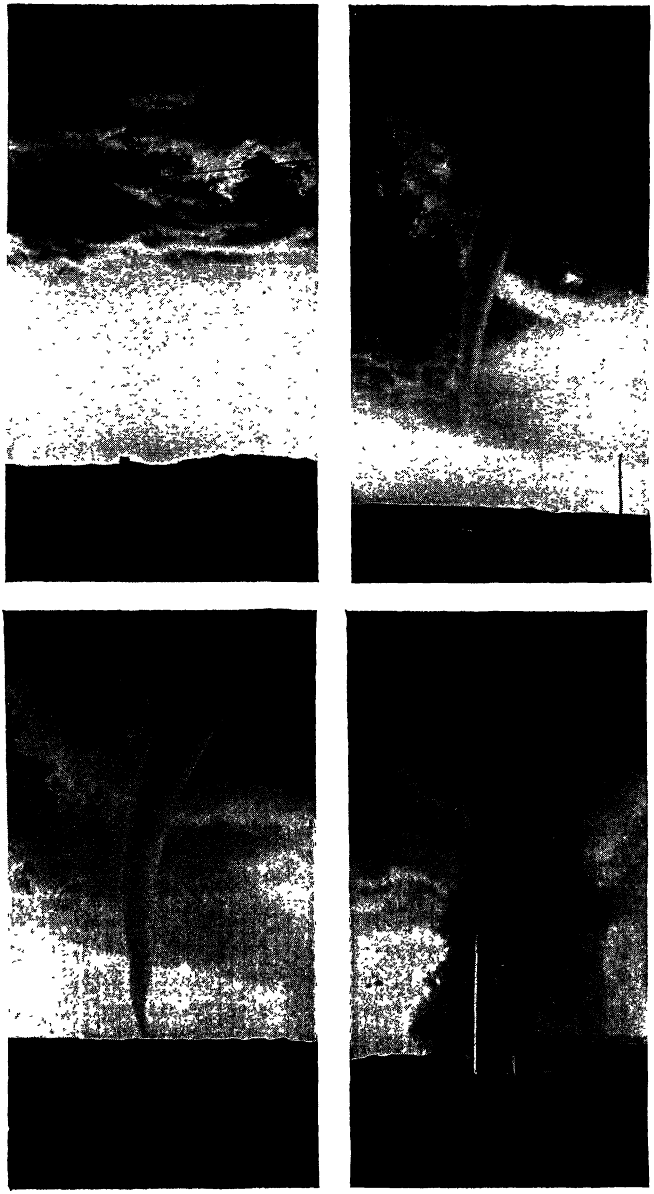


FIG. 68. Tornado near Gothenburg, Nebraska, June 24, 1930. From left to right, top and bottom, the pictures show, (1) the whirling clouds, (2) the cone dropping from the clouds, (3) the cone as it reached the Earth, and (4) the cone striking a farmhouse. Photographs from U. S. Weather Bureau

In the daytime, ceiling balloons are used. These balloons are inflated with hydrogen or helium gas to give a known rate of ascent. The time, in minutes, it takes for the balloon to disappear into the cloud is measured, and this multiplied by the known rate of ascent in feet per minute gives the height of the ceiling.

FIG. 69. Low Cumulonimbus and Cumulous Clouds characteristic of spring. Photograph from U. S. Weather Bureau

Precipitation. Three phases of water—liquid, vapor, and ice—may exist in a cloud, and water may go from the liquid drops to ice crystal by way of water vapor. Thus water accumulates around an ice nucleus until it reaches a size so large that it can no longer be sustained in the cloud and must fall to Earth.

Water clouds alone can yield no noteworthy precipitation, since no comparatively large drops can arise in them. The coalescence of drops, which is almost solely the cause of drop enlargement, only takes place abundantly for the smaller drops. Only with a low cloud height and a high relative humidity can smaller cloud drops reach the surface as a fine drizzle.

The development of precipitation as rain or hail can be illustrated by the life history of a cumulus cloud (cumulonimbus). The cloud rises at first as a pure water cloud and remains a pure water cloud even above the 32° F boundary where the temperature is below freezing. However, the drops pass into the undercooled state above the 32° F boundary. With the growth of the cloud, a critical temperature is finally attained for which the ice saturation is so low that the ice saturation suffices to introduce sublimation. Above this critical temperature boundary, ice crystals arise very rapidly as a result of violent sublimation. The undercooled drops vanish just as rapidly by evaporation. At the same time, many drops collide with the ice crystals and freeze on them.

As soon as the ascending air current in any place no longer suffices for carrying the rapidly falling ice particles, they penetrate the undercooled water cloud lying below the critical level. There they grow rapidly and finally become hailstones which, due to their size, do not melt on falling below the 32° F boundary. With a light ascending current, only small hailstones are formed, which melt below the 32° F boundary and then yield only rain. When the rain starts, only the large raindrops can reach the surface of the earth at first since the smaller ones evaporate in the dry layer of air below the cloud. Not until the air below the cloud has been soaked to the saturation point by the precipitation do the smaller drops reach the surface.

The first rain stage is characterized by particularly intense precipitation, which is dissolved by the transformation of the undercooled water cloud into an ice cloud. The ice particles grow rapidly at the expense of the drops and by an accelerated falling out. The mixing zone progresses gradually downward and finally reaches the 32° F boundary. The undercooled water cloud is then used up and, with it, the main part of the precipitation activity of the cumulonimbus is ended.

Showers are characterized not only by the suddenness with which the precipitation (rain, snow, snow pellets, etc.) starts or stops and its rapid changes of intensity, but also, by rapid changes between dark, threatening clouds and clearing of the sky. Sometimes no definite clearing occurs between the showers. Showers produce no electrical charges because the falling-out ice particles remain so

small as a result of the light upward current that with their melting the breaking of the drops is not sufficient to produce electricity.

The main feature of a *thunderstorm* is the strong upward current of air. Raindrops cannot fall through air of normal density whose upward velocity is greater than about 25 feet per second. If drops of large diameter are kept intact and attain a greater velocity than 25 feet per second with reference to the air, they are so blown to pieces that the increased ratio of supporting area to total mass causes the resulting spray to be carried aloft.

The breaking up of the raindrop is accompanied by the production of both positive and negative ions. Thus the cloud receives electrical charges which when great enough, cause the lightning spark.

Vertical velocities are frequently sufficient to cause a rate of rise of 3,000 feet per minute to be indicated on the climb indicator of an airplane. Vertical velocities exceeding 200 miles per hour probably exist in severe storms. The strong upcurrents alone are not hazardous but when they are associated with adjacent down drafts, exceedingly high velocity gradients are created. Load factors far in excess of the safety factor built into airplanes may be encountered. Spars have been cracked, ribs broken, fuselages twisted and safety belts torn loose in thunderstorms.

For the powerful tropical thunderstorms the vertical air current persists for a long time with great intensity. The first precipitation follows long after the formation of the thunderstorm. The hail stage and the first rain stage last for several hours. For small thunderstorms, on the other hand, in which the ascending current is only weak or abates rapidly, no fall of hail takes place at all, and the first rain stage also passes over quickly.

When *flying in thunderstorms*, the pilot must beware of turbulence, hail, and lightning.

The *turbulence* may extend from the ground to very high levels. When it is absolutely necessary to fly through a "squall line," it is better to fly in the thickest part of the thunderstorm rather than in the small clear spaces that may exist between thunderstorms as there is usually more severe turbulence in or along the edges of a clear space. If the clear space is a mile or more in width, the turbulence near the center will probably not be severe enough to prevent safe transit.

Not all thunderstorms contain *hail* and it is not possible to forecast hail accurately. A recent study by one of the large airlines has shown that about one out of every 400 thunderstorms has hailstones the size of walnuts or larger. A pilot comments regarding hail: "I believe that to enter a thunderstorm above 4,000 feet above the ground or below 12,000 feet is asking for trouble from hail and violent air currents."

The strongest *lightning* discharge may be conducted by a metal rod the size of a man's thumb so there appears to be little danger of serious structural damage to a metal airplane by lightning. However, several cases have been reported where radio sets have been seriously damaged with some discomfort to the radio operator. Present records show no airplane casualties due to lightning itself.

Upper Air. Upper air soundings are made to determine the pressure, temperature, and relative humidity in the upper levels of the atmosphere. The methods of obtaining data from upper levels are listed below:

Free balloons with attached instruments, which are recovered after the balloon bursts, have furnished data up to 130,000 feet. Manned balloons have gone up to 72,000 feet. Data obtained by these methods are used for research, but are usually received too late to be of use in forecasting.

Airplane observations are made with a meteorograph, containing pressure, temperature, and relative humidity elements, which is attached to an airplane and carried aloft. The usual altitude is 16,000 feet to 20,000 feet, but adverse flying weather and time required for ascent and descent limit this method.

The radiosonde or radio-meteorograph contains the same elements as the airplane meteorograph plus a radio transmitter. The whole assembly, weighing less than two pounds, is carried aloft by a free balloon. While the instrument is ascending, radio signals are transmitted to a ground receiving station where the signal is converted into pressure, temperature, and relative humidity units. When the balloon bursts, the instrument is carried down by means of a parachute. This method of obtaining upper air information is now in general use in the United States and there are about 30 stations where observations are made daily. The advantages over the other methods are, first, that it may be used in almost any type of weather, and, second, that the data are immediately available.

Exercises

1. What surface observations are taken at weather stations?
2. What important weather elements should pilots know before taking off?
3. Explain the working of maximum and minimum thermometers.
4. What is humidity, and how is it measured? What is meant by dew point?
5. Define precipitation and give the various forms.
6. What causes the winds? How is their velocity measured, or estimated?
7. What is the Beaufort Scale?
8. Give the latitudes of the major wind belts of the Earth.
9. Describe an extratropical cyclone. How big is it? Give the cloud changes that take place as one passes.
10. What are tropical cyclones? Where do they form?
11. How can one determine the approximate direction of the center of a tropical cyclone?
12. What is a tornado? Why are tornadoes not forecast by the Weather Bureau?
13. Define ceiling. How is it measured?
14. Explain how rain is formed in a cumulonimbus cloud.
15. What are the elements in which a pilot flying in a thunderstorm is chiefly interested?
16. What are radiosondes and how are they used?
17. What three meteorological elements are measured for the upper levels of the atmosphere?

☆ VIII ☆

The Clouds

Clouds are a direct expression of the physical processes which are taking place in the atmosphere. The condensation of water vapor, caused by the cooling of a mass of moist air, produces the clouds and other forms of solid or liquid water falling through the air.

In order that cloud droplets may form it is necessary to have present in the air microscopic particles called condensation nuclei. The nuclei are composed of water absorbent (hygroscopic) salt particles usually derived from products of combustion, or salt from evaporating sea spray. The atmosphere always has sufficient condensation nuclei present for the cloud droplets to form about when the air temperature falls below its original dew point at a given level.

All clouds are composed either of great numbers of small water droplets or of ice crystals, or sometimes both. It is important to the aviator to recognize the different types, for an accurate description of both type and amount plays an important part in an analysis of the weather and in forecasting the changes which are taking place. If the pilot can properly interpret the meaning of clouds, he will be able to avoid the types which are dangerous to aircraft. The international classification will be introduced here, since frequent references to clouds will be made. The importance of an international classification of clouds cannot be overestimated by pilots, since it makes cloud observations throughout the world comparable with each other. The clouds have been divided into families of high, middle, and low clouds, with special groups for clouds with vertical development, and for those in the stratosphere.

Cirrus (Ci) are detached clouds of delicate and fibrous appearance, often showing a featherlike structure, generally of a whitish

TABLE VIII. CLOUD TYPES

Name of Cloud	*Cloud Symbol*	*Height in Miles*	*Description*
			Family A: High clouds Mean lower level, 20,000 feet
Cirrus	Ci	7	Thin featherlike clouds
Cirrostratus	Cs	6	Very thin high sheet cloud
Cirrocumulus	Cc	5	Thin clouds cotton or flakelike
			Family B: Middle clouds Mean upper level, 20,000 feet to mean lower level, 6,500 feet
Altostratus	As	3½	Medium high uniform sheet cloud
Altocumulus	Ac	2½	Sheep-back-like clouds
			Family C: Low clouds Mean upper level, 6,500 feet to mean lower level close to surface
Stratocumulus	Sc	2	Globular masses or rolls
Stratus	St	¼	Low uniform sheet cloud
Nimbus	Nb		
(Nimbostratus)	Ns	¼	Low amorphous and rainy layer
Fog	F	0	Similar to stratus (not strictly a cloud)
			Family D: Clouds with vertical development Mean upper level, that of cirrus; mean lower level, 1,600 feet
Cumulonimbus	Cb	Top 4 Lower ¼	Cauliflower towering clouds with cirrus veils on top, or anvil topped
Cumulus	Cu	Top 2 Lower ½	Dense dome-shaped puffy looking cloud
			Family E: Stratosphere clouds Mean upper level, 50 miles; mean lower level 16 miles
Noctilucent		50	
Mother-of-pearl		16	Colors of mother-of-pearl

color. They take the most varied shapes, such as isolated tufts, thin filaments on a blue sky, threads spreading out in the form of feathers, or curved filaments ending in tufts. These clouds are sometimes arranged in parallel belts which cross a portion of the sky in a great circle, and by an effect of perspective appear to converge toward a point on the horizon, or, if sufficiently extended, toward the opposite point. The cirrostratus and cirrocumulus are sometimes arranged in similar bands as well. The cirrus are the highest of the common clouds and are formed of ice crystals.

Cirrostratus (Cs) gives the appearance of a thin, whitish sheet

of cloud sometimes covering the sky completely and giving it a milky appearance (then called *Cirronebula*), but at other times presenting a more-or-less distinct formation like a tangled web. This sheet often produces halos around the Sun and Moon because it is made up of ice crystals.

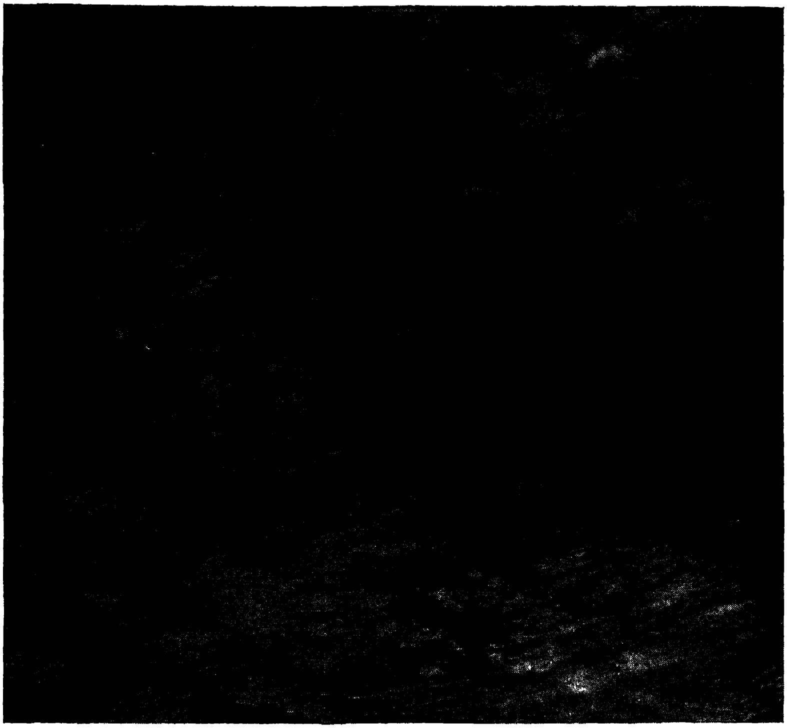


FIG. 70. Tufted Cirrus Clouds. Photograph by F. W. Kent

Cirrocumulus (Cc) are small globular masses or white flakes without shadows or showing very slight shadows, arranged in groups and in lines, giving rise to the term "mackerel sky." These clouds are formed of ice crystals.

Altostratus (As) clouds give the appearance of a thick sheet of gray or bluish color, sometimes forming a compact mass of dark gray color and fibrous structure. At other times the sheet is thin, resembling thick cirrostratus, and through it the Sun or the Moon

may be seen dimly gleaming as through ground glass. This form exhibits all changes peculiar to cirrostratus, but from measurements its average altitude is found to be about one-half that of cirrostratus. Nonfibrous altostratus is often undulated or festooned. These clouds are formed of ice crystals, and may give rise to rain or snow.

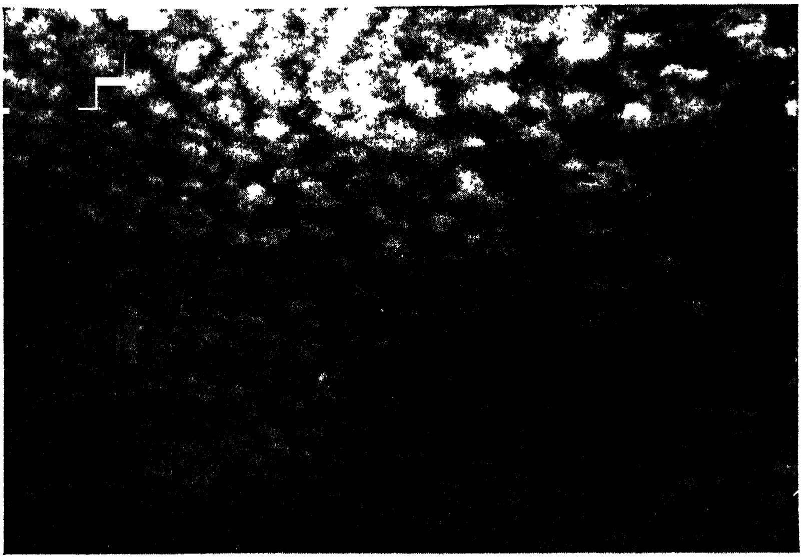


FIG. 71. Cirrocumulus Clouds. Photograph by F. W. Kent

Altocumulus (Ac) clouds are large globular masses, white or grayish, partially shaded, arranged in groups or lines, and often so closely packed that their edges appear confused. The detached masses are generally larger and more compact, resembling stratocumulus at the center of the group, but the thickness of the layer varies. At times the masses spread themselves out and assume the appearance of small waves or thin, slightly curved plates. At the margin they form into finer flakes resembling cirrocumulus. They often spread themselves out in lines in one or two directions. Small altocumulus may also be described by the term "mackerel sky." They are formed of both ice crystals and water.

Stratocumulus (Sc) are large globular masses or rolls of dark clouds often covering the whole sky, especially in Winter. Generally,

this cloud presents the appearance of a gray layer irregularly broken up into masses, of which the edge is often formed of smaller masses, often of wavy appearance resembling altocumulus. Sometimes this cloud form presents the characteristic appearance of great rolls arranged in parallel lines and pressed up against one another. In their centers these rolls are of a dark color. Blue sky may be seen through the intervening spaces, which are of a much lighter color. Stratocumulus clouds may be distinguished from nimbus by their globular or rolled appearance, and by the fact that they are not generally associated with rain. They are formed of droplets of water and occasionally yield precipitation.

The *stratus* (St) is a uniform layer of cloud resembling a fog but not resting on the ground. When this sheet is broken up into

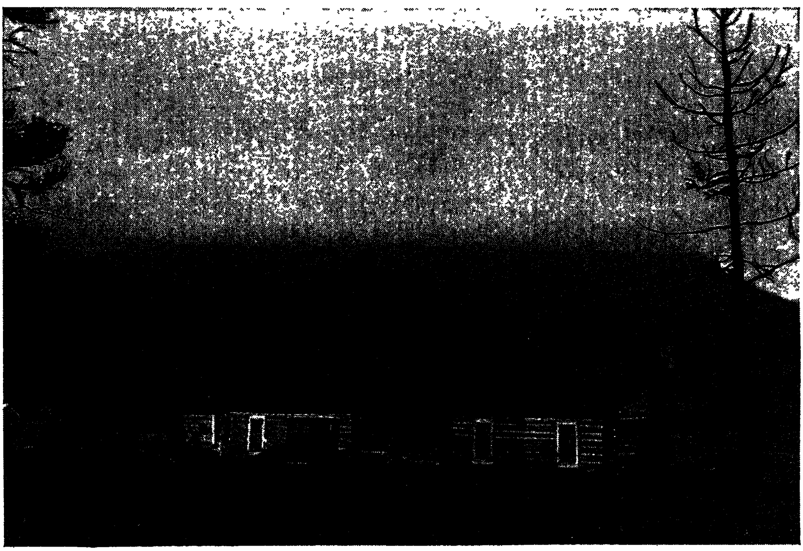


FIG. 72. Low Stratus Cloud Enveloping Upper Part of Hill. Photograph by F. W. Kent

irregular shreds in a wind, or by summits of mountains, it may be distinguished by the name *fractostratus* (Fs). A stratus cloud may be undulated or festooned, even though "uniform." The low height of about one-fourth mile for stratus distinguishes it from non-fibrous altostratus. The stratus is formed of tiny droplets of water, and may produce a "drizzle."

Nimbus (Nb), or the *rain cloud*, is composed of a thick layer of dark clouds without shape and with ragged edges, from which steady rain or snow usually falls. Through the openings in these clouds an upper layer of cirrostratus or altostratus may be seen almost invariably. If a layer of nimbus breaks up into shreds in a strong wind, or if small loose clouds are visible floating underneath a large nimbus, the cloud may be described as *fractonimbus* (Fn) or what sailors call "scud." Note that all rain clouds are not nimbus nor cumulonimbus, but only those having the characteristics as defined. Altostratus and stratocumulus frequently yield rain or snow, while precipitation occasionally reaches the ground from altocumulus, cumulus, and possibly others.

Fog (F) is any type of suspended condensation at the ground level. It consists of very small water droplets, or ice particles, and restricts the visibility seriously. A fog is essentially the same as a low stratus cloud, but it is at the ground level and so is not a true cloud.

Cumulus (Cu), commonly called the *woolpack clouds*, are thick clouds of which the upper surface is dome-shaped and exhibits protuberances while the base is horizontal. These clouds appear to be formed by a diurnal ascensional movement of air, which is almost always noticeable. When the cloud is opposite the Sun, the surfaces facing the observer have a greater brilliance than the margins of the protuberances. When the light falls aslant, as is usually the case, the clouds throw deep shadows. When the clouds are on the same side of the observer as the Sun, they appear dark with bright edges.

True cumulus has well-defined upper and lower limits, but in strong winds a broken cloud resembling cumulus is often seen in which the detached portions undergo continual change. This form may be distinguished by the name *fractocumulus* (Fc).

Typical cumulus over land areas develops on days of clear skies from currents of diurnal convection; it appears in the morning, grows, and then more-or-less dissolves again toward evening. This type is known as "fair-weather" cumulus or *cumulus humilis.*

Cumulonimbus (Cb), the thunder clouds or shower clouds, are heavy masses rising in the form of mountains, turrets, or anvils, generally surmounted by a sheet or screen of fibrous appearance (false cirrus) and having at the base a mass of cloud similar to

nimbus. From the base local showers of rain or snow (occasionally of hail) usually fall. Sometimes the upper edges assume the compact form of cumulus and form massive peaks around which delicate "false cirrus" floats. At other times the edges themselves separate into a fringe of filaments similar to cirrus clouds. This last form is particularly common in spring showers. The front of thunder clouds of wide extent frequently presents the form of a large arc spread over a portion of a uniformly brighter sky.

FIG. 73. Cumulonimbus Clouds, Showing Precipitation. Photograph from U. S. Naval Air Station, San Diego, California, Through U. S. Weather Bureau

The clouds in this last group are very rare, and because of that they are of no value in weather forecasting. However, they are included here to make the discussion of clouds more complete.

The *noctilucent*, or "night-shining," clouds are so-called because they can be seen in full sunlight long after the stars appear. Because of their great height they may be seen in full sunlight near the close of visibility of the twilight glow. They are noticed most easily by people in rather high latitudes who have twilight lasting all night in the summer months. These clouds first attracted serious attention when they appeared in greater numbers than usual fol-

lowing the great eruption of Krakatoa in 1883. Since that time they have been observed on many occasions in northern Europe and in northern Canada.

The most accurate measurements of the height of noctilucent clouds have been made by Störmer, a Norwegian observer of the aurora. Occasionally, his men, watching for auroral displays, have noticed these clouds low in the north and photographed them with the auroral cameras. The photographs from two stations make possible an accurate determination of the real height in miles.

The *mother-of-pearl* clouds are so called because they are filmy clouds which show the colors of mother-of-pearl. They are rarely seen, but have been observed from Wisconsin and from Iowa, as well as from Canada and Europe.

Wind Direction from Clouds. It is well known that as a result of surface friction, wind velocity normally increases with altitude throughout the layer from the ground up to about 2,000 feet. The upper portions of clouds within this layer will normally move faster than the lower portions. Therefore, careful scrutiny of the *motion within lower clouds* will at once give the wind direction at the level observed. Only as much of the cloud as will give this relative motion, perhaps a fragment apparently a yard long, need be watched. To the benefit of a pilot above the clouds, the tops of clouds give better indications of wind direction than the bases.

When the increase of wind velocity with altitude is sufficient to cause turbulence, the cloud will be filled with vortices, or *curls*. The tops of the larger *cloud curls* move with the wind, and give an indication of the wind direction. The rising portion of a curl is its most dense portion. When the curl turns downward, it is heated at a rate which tends to dissipate the sinking portion. Visible curls are at the surface of the clouds and are penetrating unsaturated air which also tends to dissipate the cloud. The result is protruding curls which are well defined in their rising portions. The dissipating curl or "hook" has a very characteristic appearance and may be seen at distances from a few yards up to more than 75 miles depending upon the size of the curl.

With an increase of wind velocity upward, the "hook" points in the direction of the wind. When wind velocity decreases with elevation, the curls will rotate opposite to their normal direction and the hooks, reverse curls, will point upwind. If the pilot is not lost,

it matters little which way the curls are rotating as they will always indicate the altitude within the cloud levels at which the wind is most favorable.

The *shape of clouds* often indicates wind direction. Cirrus clouds are strung out in the direction of the wind with the forward portion

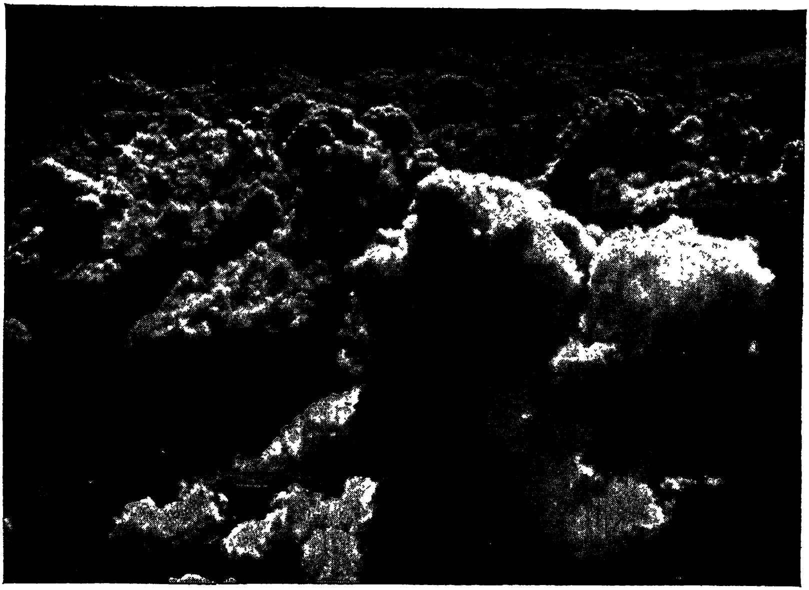


FIG. 74. Towering Cumulus Clouds Seen from Above. Photograph from U. S. Weather Bureau

often apparently raised, sometimes forming a tuft. Their fibrous appearance readily reveals the direction in which they are moving. Distinct angles in the fibers indicate a change of wind direction at that point and are a sign of convergence. Other stratiform clouds are the most difficult clouds from which to determine wind direction by their shape. When they are in solid layers, the best information may be gained from a detailed study of their upper and lower surfaces. When broken, or isolated, the portion in the strongest wind will move ahead of the cloud, giving it a leaning appearance.

When the wind increases aloft, the upwind edge of cumuliform clouds is well defined; it slopes upward and forward with the wind. On this side of the cloud only the rising portions of the curls are visible. The downwind edge has a frayed appearance and also

slopes generally upward and forward. On this edge the dissipating portions of the curls are visible. The whole cloud has a tilt down-wind and a swept-over appearance as though it had been lightly brushed over. Rapidly building cumuli are usually well defined on all edges although by far the major portion of the curls, even on the upwind side, have their characteristic rotation. The large curls give the impression of a bull with its head lowered for a charge. Very rapidly building cumulus is identified by its columnar structure as well as the relative motions which are plainly visible from the ground or the air.

When water droplets begin to change to ice crystals at the 32° F level or above, the cloud begins to take on a fibrous appearance, curls are less well defined and larger features become more important. Beneath a stable layer the cloud spreads out in all directions forming the anvil of the thunderhead, but the winds aloft will cause the down-wind portion of the anvil to be greater in extent, often stringing it out into cirrus. Wind direction at the top of a thunderhead may readily be determined with reasonable accuracy at distances greater than 100 miles.

The *orientation of clouds* is still another means of determining wind direction. Clouds often appear in rows or exhibit a slanting parallelism. Stratiform clouds sometimes appear in well defined rows or rolls. These rolls are really waves along a minor discontinuity surface above and below which the wind may be in the same or different directions. These waves are known as Helmholtz waves and usually are only a few hundred yards in amplitude. The bands of clouds run along the crests of these waves with the clear air in the troughs. Much smaller waves frequently occur. Since the waves form at right angles to the resultant wind direction, the rows of clouds are perpendicular to the wind.

Rows of cumuliform clouds generally run with the wind, with the more highly developed clouds upwind, contrary to the appearance of stratiform clouds. A possible explanation is that when the cumuliform clouds do form in rows, only a small portion of the sky is usually covered by them. This would indicate either that only streaks of the air mass could support cumulus clouds or that exceptional convective activity existed over a relatively small area. The tilting of individual clouds gives a slanting parallelism to a whole group of clouds.

The best view for determining wind direction from clouds is crosswind. When viewed up- or downwind, the line of sight is parallel to the plane of rotation of individual curls and is in line with any general tilting of the clouds; hence, these features are obscured. Clouds do have a characteristic appearance for crosswind, upwind, and downwind views. The downwind view reveals well-

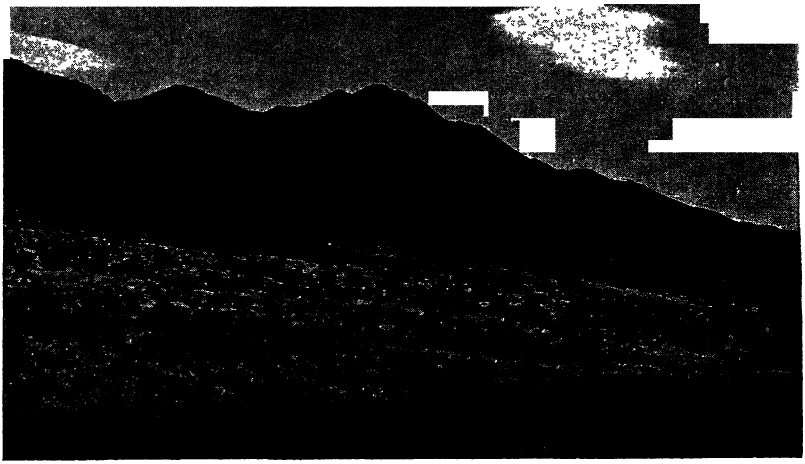


FIG. 75. Stationary Altocumulus Cloud formed in Lee of Mountain. Although the cloud is stationary, the air within is in motion, the cloud constantly being formed by condensation on one side, and being dissipated by evaporation on the other. Photographed by F. W. Kent.

defined surfaces sloping up and away from the observer, while the upwind view shows the more ragged, frayed, and darker portions of the clouds.

Wind direction determination from a group of clouds is more reliable than from an individual cloud. The shape, orientation, and motions of clouds may be determined by a single glance and the entire visible portion of the atmosphere may be seen very quickly. It is advisable to scan the entire horizon before coming to a definite conclusion as to wind direction or the relative motion at various levels. Experience has shown that optical illusions play an important part, especially with beginners. A determination made from a single cloud may be correct to within only 180°. An average direc-

tion, determined upon after glances have been made in several directions, will bring the possible error of angle down to small limits. Quite often several glances will yield no definite information, but it is rare that a search of the entire sky will not give the information that is sought.

A well-defined edge of a layer, or mass of clouds, is usually perpendicular to the direction of motion of the clouds. Advancing clouds have an appearance of strength that trailing clouds do not have. Clouds near the leading edge may be seen to grow and thicken while the trailing clouds get thinner and dissipate. Not only wind direction but the direction of a storm center or a clearing area may be learned from the orientation and appearance of the edge of a cloud mass. For example, a hurricane was known to exist in the Gulf of Mexico, but its location was not known because of the lack of ship reports. The leading edge of the advancing cirrus clouds formed an arc that was clearly visible from the ground when it was about 150 miles from Randolph Field, Texas. A radius drawn mentally to this ring, together with the estimated distance of the cirrus clouds ahead of the center, gave the location of the storm center at about 400 miles south-southeast of Randolph Field. Later, map data showed this estimate to be approximately correct. A series of such observations on a different hurricane gave the direction of motion of the storm center, as well as the distance away.

The same principles used with clouds may be used with smoke, dust, or thick haze. In thick haze, vortices may be seen from the ground up to the base of the clouds. Curls that originate below the saturation level and extend above that level will be cloud in the upper part and haze in the lower portion. The direction that smoke columns lean is an important clue and the stringing out of smoke from a fixed source is almost an ideal wind indicator.

At night, surface cooling stabilizes the air near the ground and reduces surface velocities considerably; so that under an existing pressure gradient winds at about the 2,000 foot level pick up proportionally. If low stratus exists, the resulting vertical velocity curls may be seen easily in moonlight. Cirrus, and other clouds above the convective layer, have the same general appearance at night as in the daytime except that they appear to thin out and quite frequently disappear entirely at night.

Cloud Formation and Dissipation. Very low clouds will always be one of the greatest hazards to aviation because they hinder the landing of aircraft. Higher clouds are hazards when they limit visibility or cause precipitation, and thereby cause malfunctioning of radio, contain severe turbulence, thunderstorms, or icing conditions. They also contribute to a hazard when they aid in the formation of very low clouds.

Clouds *form* when the air is cooled sufficiently. The air may be cooled as a result of lift, or radiation, or both. Irregular lift, as in convections, forms cumuliform clouds. They increase over land during the day. Hence, when the clouds that appear first are stratiform, there is strong evidence that there is overrunning, and a storm front is approaching. Continued increase in the thickness of the stratiform clouds or the appearance of several layers of clouds and especially precipitation indicate that the front is near. Many pilots have understood these signs but yet have continued on until one of the many possible hazards has made further progress in the given direction impossible. Then, not knowing the situation,

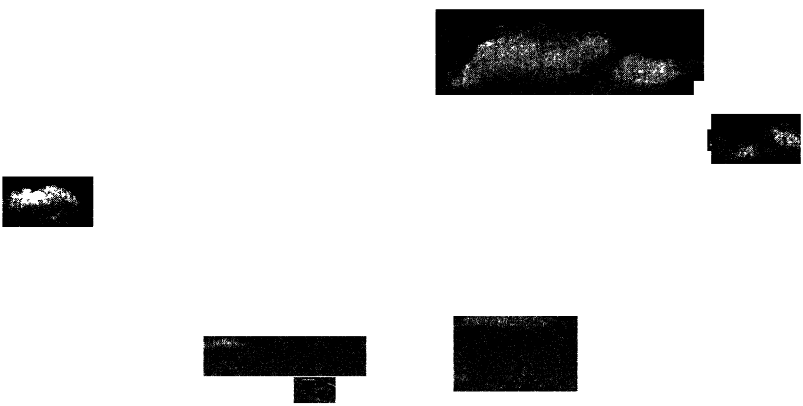


FIG. 76. Fair Weather Cumulus Clouds. Photograph from U. S. Weather Bureau

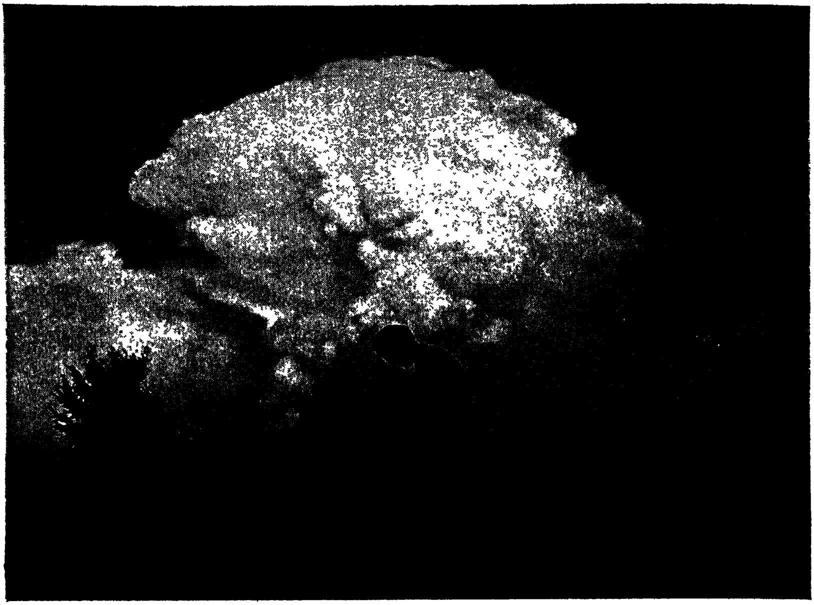


Fig. 77. Cumulonimbus Cloud. Photograph by F. W. Kent

Fig. 78. Cumulonimbus Cloud in Fig. 77 Five Minutes Later. Photograph by F. W. Kent

they have not known which way to turn. "Turn back" is still a good rule, but not an infallible one, because clouds do move and form. Clouds may form at any time during the day or night because the wind blows 24 hours a day.

Cumulus clouds *dissolve* upon the approach of a warm front surface. Cirrus or cirrostratus clouds means the shrinking and flattening out of cumulus clouds. They undergo a complete transformation and become stratiform in character. The same effect is produced in the evening when diurnal convections cease. The typical clouds formed by this process are stratocumulus and fractocumulus, or fractostratus.

Low stratus clouds not in a frontal zone may break up after sunrise and disappear later in the day. Ceilings will usually lift until the diurnal maximum temperature is reached. Over land, both main types of clouds, except fog and low stratus, tend to dissipate at night. Over water, the convective clouds increase at night and decrease during the day.

The Trend. What the pilot wants to know concerning his route and destination is not only what exists along the route yet to be covered, but what the weather will be at the time of arrival. In other words, the *trend* of the weather is the desired information. One of the best ways to determine the trend is to determine whether the cloudiness is increasing or decreasing. A check may be made by picking out an individual cloud and carefully noting what is happening to it, or by estimating at intervals the amount of cloudiness in tenths of sky cover, then comparing estimates.

There are several other methods, such as noting the change in the type of cloud, the beginning or ending of precipitation, or the change in type of precipitation, keeping in mind the time of day in relation to what is expected to happen. Another method notes whether the air is becoming cooler or warmer, whether the ground is wet, dry, or snow covered, whether the air has been made stable or unstable by recent passage over bodies of water. It is also, most important to notice whether there is a cold or warm air mass and in which direction it is moving, together with its relation to adjacent air masses or bodies of water.

The navigator should watch the cumulus clouds. If they are the typical fair weather cumulus, there is no danger of a storm. If they

are the flat bottom type with towers, there is possibility of a storm. If the towers are growing, and the top spreading out into a cirrus type, precipitation is probable.

Fog. Fog, haze, and low stratus have always been hazards to aviation. Instrument flying, radio aids, and celestial navigation have largely solved the difficulty for flying between terminals. Various methods have been invented to make landing possible when the ceilings and visibilities are very low or zero. However, they require special equipment and training, either or both of which may not be available to the pilot at a critical time; the hazards remain.

Obviously, the best policy is to avoid the necessity of landing where the ceiling and visibility are below safe limits. This requires expert forecasting before take-off, and the constant attention of the navigator or pilot during his flight. It is a waste of time and material to take off for a given destination, and then have to turn back or go to some other landing place. In fact, it is not always possible to return to the point of take-off, because the weather at any given locality does change.

A fog may be defined as a condition of poor visibility at the ground, resulting from suspended water droplets or ice particles. The condition must be at the ground, thus excluding a cloud, and must also be due to suspended condensation products, so that falling precipitation is excluded. As we shall see presently, ice crystal fogs sometimes are observed and these can be regarded as true fog. Haze, on the other hand, is not due to water vapor condensation products and is not included in the above definition. Haze is usually due to the presence of solid suspended particles.

The nuclei which are effective in producing a fog are of the hygroscopic type, being often very small particles of sea salt, or in the vicinity of industrial activity, combustion products. Apparently we may get fog, even though the relative humidity is only 80 per cent, if the "industrial" nuclei are present. It is important, therefore, in forecasting fog, to study the location and ascertain whether or not industrial pollution of the air is a factor.

Granting that there are sufficient condensation nuclei present, it is clear that the relative humidity must be increased to some critical level. This may be done either by increasing the moisture, or by cooling the air until the amount of moisture already present is

sufficient to produce saturation with respect to the nuclei. Generally the second method is the important one, although probably the first often does take place.

The *monsoon type of fog* is produced by warm air blowing from land onto a relatively cool water surface. The fog is produced by the cooling of the lower layers of air from contact with water. In order to produce this type of fog, it is necessary to have the wind movement from land to water. If the wind is too great, however, it will lift the fog into a low stratus cloud. There is, thus, a maximum wind velocity which is effective for producing this type of fog.

The monsoon fog is found chiefly over water surface, but since it forms not far from land, the breeze may bring it inland temporarily. Thus, outlying points on the coast may experience it rather often, but it may reach stations farther inland. This situation may sometimes last for several days. On the whole, this is a persistent type of fog.

A *sea fog* is produced by air flowing from a relatively warm ocean to a region where the ocean surface is cold. It may be found at any season, but tends to have a maximum during the Spring. Its formation is favored by the fact that, over the sea, the moisture content of the air is high; so that a slight decrease in the temperature of the surface below is sufficient to produce this type of fog. Sea fog is found near the Newfoundland Banks, where the warm water of the Gulf Stream is found next to the cold coastal waters from the north. It is found also in a region off the east coast of Asia involving the Japanese current. Sea fog is formed also over the water off the California coast, where there exists a cold stream of water parallel to the continent. Here it is brought inland by the wind movement in the form of fog or low stratus. In the Arctic regions, fogs of this type are very prevalent.

The remarks made previously in regard to the wind velocity also apply to sea fog; wind may lift the ceiling and produce a stratus cloud.

If cold air moves upon a warm water surface, it is possible to get a *steam fog* as a result. Rapid evaporation from warm water takes place, and as the moistened air rises it becomes chilled by the colder air, and condenses into cloudlets of visible moisture. Generally, such a process cannot produce a dense fog since the conditions are such as to cause a vertical mixing, which dissipates the fog as

rapidly as it is formed. If, however, there is a strong inversion of temperature near the surface, it is possible for the fog to accumulate beneath it, and the visibility may be reduced greatly.

In the great plains region of the United States, there is a gentle rise of the ground to higher elevations toward the west. If an east wind carries air of sufficient moisture, it will be cooled as it moves up the slope, eventually causing saturation and the formation of an *up-slope fog*. This type of fog is formed more quickly the more rapid is the up-slope transport, and can therefore exist in spite of high wind velocities, being different in this respect from other types of fog which we have studied.

In a *radiation*, or *ground fog*, the cooling of moist air to the condensation point takes place by radiation from the ground below, the air above being cooled by contact with the ground.

Ground fog is of a more local nature than the types previously considered. Usually it forms in low places, since elevated locations are influenced by drainage of the cold air as it is formed. Generally a ground fog is fairly shallow and does not obscure the sky completely, the moon and brighter stars being visible through it. This kind of fog is, generally speaking, favored by light winds, since it is easily dissipated by appreciable turbulence. It usually is dissipated shortly after sunrise.

Frontal fogs are, as a rule, formed before warm and cold storm fronts, and are of limited extent as compared with those previously discussed. The prefrontal warm front fog is common in the eastern United States, where it is principally a winter phenomenon. The prefrontal cold front fog is formed if a cold front advances against a mountain slope. The air in front may be pushed to higher and higher levels by the cold air, until fog formation results in the warm air.

Icing of Aircraft. The two fundamental requirements for the formation of ice on aircraft are: the plane must be flying through visible water in the form of precipitation or cloud, and the temperature of the liquid droplets must be below 32° F. Ice does not form on aircraft flying through clouds formed of ice crystals.

Supercooled water droplets exist in a majority of clouds when the temperature of the cloud is below 32° F. It has been found that water clouds can form at temperatures below 32° F, but at temperatures from +5° F to −4° F there is a tendency toward ice

crystal cloud formation, and below −4° F clouds in the process of formation will be composed mostly of ice crystals.

Water clouds can, however, be cooled to very low temperatures, and have been found even at −60° F in the polar regions. Water in the liquid form at temperatures below 32° F exists in a very unstable state, and when disturbed will rapidly be changed at least partially into ice. The impact of the droplet with various parts of the airplane disturbs it and begins the freezing process. It is possible, because of the expansional cooling of air over the airfoil, to be flying in air which has temperatures of 32° F to 35° F and have ice form.

Clear ice, or *glaze,* is a clear, hard, amorphous ice. It is an important danger to planes not equipped with wing de-icing and propeller anti-icing equipment, since it builds out in the form of a mushroom

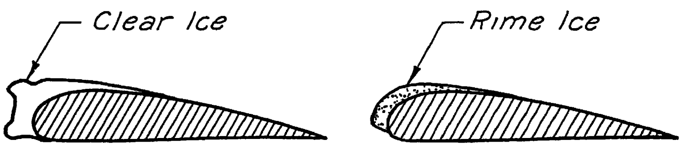


FIG. 79. Ice Formation on an Airfoil

and destroys the airfoil and thus decreases the lift and the propeller efficiency. Clear ice forms in clouds with large drops or in "freezing rain." (See Fig. 79, left.)

Rime is an opaque, whitish ice with a granular texture. It is not so tenacious and it does not destroy the airfoil. It is easily broken off by wing de-icers of the pneumatic type on the leading edges, but has a tendency to stick to the wing back of the de-icer "boot." Its roughness increases the drag and tends to decrease speed of ships with high wing loading. (See Fig. 79, right.) Usually, heavy coatings of ice on aircraft consist of a mixture of rime and clear ice.

Frost is small separate crystals of ice. Frost is not an important danger while in flight, but when it forms on a plane on the ground it may impede take-off. Frost should always be removed before take-off.

Ice forms on the *wires*, forward edges of *struts* and *radio masts*, and the leading edges of *wings, propeller,* and *control surfaces.* It increases the load of the airplane and increases the parasitic drag

of the struts, wires, and appendages. It reduces propeller efficiency and power output and the aerodynamic efficiency of the control surfaces, thereby reducing controllability and the aerodynamic efficiency of the wings, which reduces lift.

Of these effects, by far the most important is the last. However, it will be noted that all the effects are additive in impairing the flying qualities of the aircraft. The lift of the airplane is so reduced that frequently it will not be able to fly, even with normal load and full power. At the same time the propeller power output falls off, the load increases from the weight of the ice, which by itself might not prove too great an overload, and the parasitic drag increases and absorbs more than its normal share of power. Added to this is the fact that the pilot is frequently flying by instruments through bumpy or turbulent air, where the logginess incident to inactive control surfaces makes the airplane difficult to handle.

Ice will continue to form as long as the airplane remains in the danger area, spreading from the leading edges of the surfaces back to the trailing edge, and finally in some cases forming icicles extending beyond the surface proper. The icing of the propeller will spread over the entire length of the blade and form irregularly on the spinner. Finally the fuselage will also become iced, if by that time the airplane has not already been forced down.

Icing in the throats of venturi tubes and over pitot tubes will cause *air speed indicators, flight indicators,* and other venturi actuated instruments to cease functioning, just at the time when conditions of visibility and controllability make their proper functioning essential. *Icing* on the throat of *carburetor venturis* may cause malfunctioning of the engine. On supercharged engines, icing of carburetor venturis may occur at temperatures well over 32° F, perhaps up to 45° F.

It is presumed that eventually control surfaces would jam, although this has not been proven since the previously mentioned effects have invariably forced the airplane to descend prior to this stage. Instances have been reported of *excessive vibration* caused by ice deposits on airplanes. In this way structural failure may occur in either internally or externally braced types of airplanes.

Icing is bad in a region of *freezing rain* beneath a temperature inversion. The moisture, in falling from temperatures above freezing in the clouds, passes through the cold air below and undergoes

cooling. In cases of freezing rain the pilot should climb into the warm air where the rain temperature will be above freezing. Icing is encountered when flying through light *mist, fog,* or *clouds* at *dangerous temperatures.* The droplets are relatively small and favorable to the formation of rime. However, they will, if sufficiently dense, form clear ice or mixtures of clear ice with rime. Sometimes, also, sleet or snow will be imprisoned in the ice itself.

The vertical motions which give *cumuliform clouds* their characteristic appearance, support large droplets and make the formation of *clear ice* more frequent in this type of cloud. Cumuliform clouds form in unstable air; therefore, clear ice is more apt to form in clouds in unstable air than in stable air.

About 85 per cent of the observed icing of aircraft has occurred along *warm or cold storm fronts.* Typical *warm* front clouds are stratiform in character and rapid movement up the warm front may contain only a small vertical component, but the small lift of a great mass of warm air may produce thick cloud systems and heavy precipitation, with larger drops than otherwise might be expected from stratiform clouds. Clear ice, or a combination of clear ice and rime, may result. Warm front cloud systems are often of great extent, thereby causing flights in them to be of long duration with a subsequent increased danger of severe icing.

Cold fronts are associated with cumuliform clouds, and hence are more apt to cause clear ice. The cold front cloud system is relatively narrow compared to the warm front system so that the period is shorter during which icing may take place on a flight across the frontal zone. However, the combination of clear ice and a higher rate of accumulation makes cold front icing zones extremely hazardous.

Icing is more probable and more severe in *mountainous areas.* Mountain ranges cause upward motions on their windward side in air that is moving across them. Vertical motions over the ridges will support large droplets. The most severe icing will take place above the crests, and to the windward side of the ridges. The zone extends usually about 4,000 feet above the tops of the mountains, but in the case of unstable air may be even higher. The movement of a storm front across mountains brings together two important factors that aid in the formation of icing zones. A study of icing in the western United States has shown that almost all of the ice cases

occurred where the air was blowing over a mountain slope, or up a frontal surface, or both.

Exercises

1. Why is an international classification of clouds important in aviation?
2. Learn the heights and be able to identify the cloud types of the international classification.
3. What are the two stratosphere clouds?
4. What are the limits of the altitudes of the families of clouds?
5. How can wind direction be obtained from clouds?
6. What other factors are useful in estimating wind direction?
7. Explain the formation of clouds. How do the different types change to other types?
8. What does the pilot mean by trend of the weather?
9. Which clouds are most hazardous to aviation?
10. What is fog? How is it formed?
11. Name the different types of fog. Where and why do fogs form?
12. When does ice form on aircraft?
13. What are supercooled water droplets?
14. What are the two chief types of ice formation? Why is ice so dangerous to the pilot?
15. Where does ice usually form on the plane?
16. Why is icing worse along fronts and in mountainous areas?

☆ IX ☆

Weather Forecasting

Everyone is familiar with the weather forecast as published in the daily paper, or given over the radio. Some are familiar with the airway forecasts, which give additional information on the probable weather conditions.

The United States Weather Bureau. Intelligent forecasting for a region is possible only after a thorough study of the present weather conditions and recent changes over that region. For this work the U. S. Weather Bureau maintains a central office at Washington, D.C., and numerous offices and stations throughout the nation, including Alaska, Hawaii, and Puerto Rico. There are over two hundred first-order stations at which complete meteorological records are kept. Most of these receive daily reports of observations and issue forecasts and bulletins on the weather. In addition to the first-order stations, there are second-order stations which make daily telegraphic reports for the weather forecast service. There are third-order stations which telegraph daily weather observations at certain times only for special purposes. There are river substations, for keeping records on the flow of rivers and on precipitation; crop substations; climatological substations with their cooperative substations; and airway substations.

One of the most important services of the Weather Bureau is the *climatological* service, which is carried on in cooperation with the Department of Agriculture. The first-order stations of the Weather Bureau keep a complete record of meteorological data such as clouds, state of weather, pressure, temperature, humidity, wind direction, wind velocity, and precipitation.

To establish better the features of the climate in various localities of the country, cooperative substations, well distributed over the

country, have been established. There are about 4500 such stations in the country, often only 20 to 30 miles distant from one another. These cooperative stations are not equipped with recording instruments, but they are equipped with rain-gauges for measuring precipitation and with standard shelters for maximum and minimum thermometers. The cooperative observer reads the thermometers and measures the amount of precipitation once each day, generally in the evening near sunset. He also records the state of cloudiness during the day, the prevailing wind direction, and weather phenomena of special interest, such as severe thunderstorms, hail, windstorms, and frost in Spring and Autumn. Occasionally, some of the cooperative observers wire morning observations to a central office at certain times of the year to give more data for forecasting. These observers serve without pay.

Among special services of the Weather Bureau are the following: There is a *forest fire* service, since the weather is an important factor in controlling these fires. Many of the forest ranger stations are equipped for making meteorological observations. There are *river and flood* substations, since the forecasting of floods is very important for certain parts of the country. There is the *hydrological* service, which maintains a record of the precipitation in river basins. This service has about 1000 additional recording rain-gauges and numerous nonrecording rain-gauges to make the records of precipitation in the drainage basins of the rivers more complete than would be possible with the climatological stations alone. There are stations where records of the evaporation each day are kept, and stations where the solar radiation is measured.

An important branch of the Weather Bureau is the *marine meteorological* service. A considerable number of ships make weather observations each day at Greenwich mean noon. The observations must be made at that Greenwich time, whatever the local time may be. In normal times, within certain areas, the daily weather observations are reported by radio. From these reports the central office of the Weather Bureau can make daily weather maps of the North Atlantic and the North Pacific oceans. These daily weather maps are essential in forecasting the tropical cyclones or hurricanes of the West Indies, and they are also useful in forecasting the weather of the Hawaiian Islands and of both the Pacific and Atlantic coastal areas. The more complete reports turned in by

the masters of the ships are used by the Navy Department in preparing monthly pilot charts.

The *aeronautical,* or the *airway meteorological* service, has become one of the most important branches. A successful solution of the weather problem for aviation requires, first of all, a dense network of surface and upper-air observation stations, manned by trained observers, and the rapid transmission of frequent reports from these. Secondly, it requires a technical staff of employees at terminal airports to prepare frequent weather maps, upper-air charts, and diagrams from which a picture of the changing weather situations may be prepared. Thirdly, it requires competent meteorologists to analyze the current weather conditions, anticipate the development of new situations, compute the movement of pressure systems, and to issue, on the basis of these, short-period forecasts for the route to be flown.

In constantly endeavoring to maintain as complete a service as possible, the Weather Bureau has established several hundred stations, at fairly regular distances apart, along the civil airways in the United States, Alaska, and Hawaii, and, in addition, a large number of stations rather uniformly distributed off the airways for reporting weather. (See Fig. 80.) Reports are collected by telephone, radio, and teletype systems. There are well-distributed stations, equipped for taking upper-air wind observations, and additional stations at which upper-air observations are made by airplanes and by instruments, which are carried aloft by balloons and report conditions through the medium of radio signals (radiosondes). At important airway terminals, qualified meteorologists of the Weather Bureau are on duty 24 hours a day, charting and analyzing weather reports and discussing the meteorological conditions with pilots.

Weather observations are taken hourly throughout the 24 hours at most of the stations located on civil airways. Special observations are taken at these stations whenever marked changes in weather conditions occur. At stations located off the airways, observations are taken every 6 hours, and every 3 hours at a few designated to do this. Observations generally consist of ceiling, that is height of cloud layer above the ground, in feet; sky conditions; visibility in miles; weather conditions, including precipitation, squalls, etc.; obstruction to vision, such as fog, haze, and smoke; temperature; dew point; wind direction and velocity; barometric pressure, and pres-

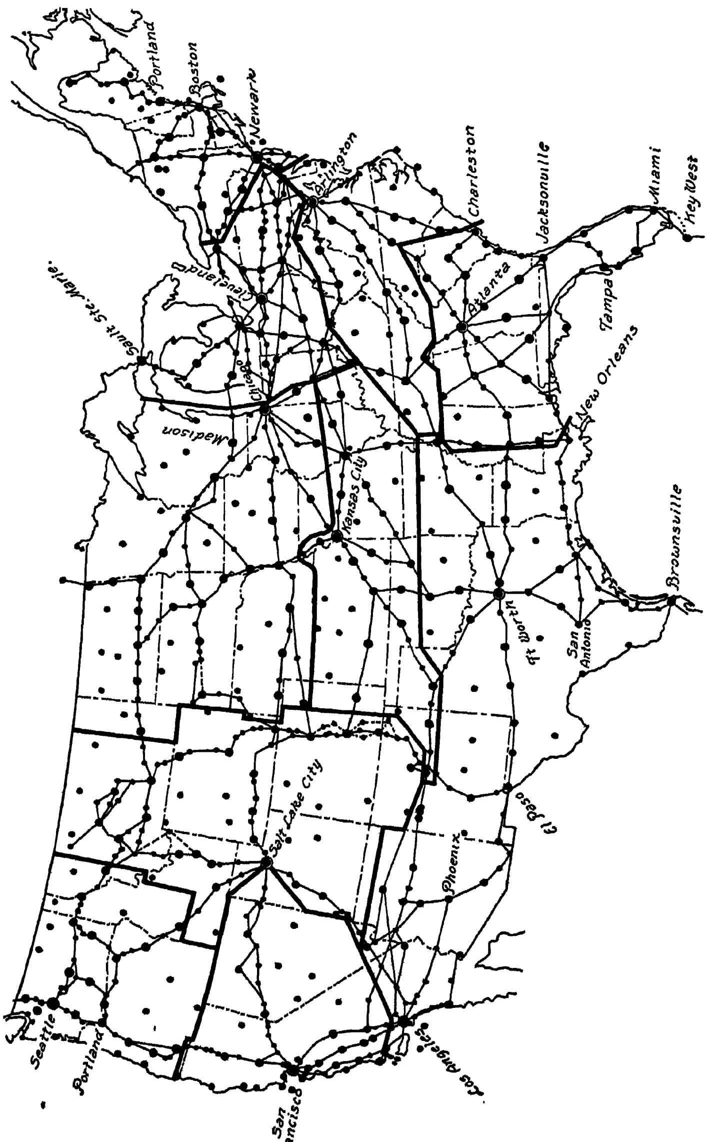


FIG. 80. Airway Meteorological Stations in the United States. Each dot represents a station

sure change tendency; amount, type, and direction of clouds, and other miscellaneous information as thunderstorms and line-squalls. Reports from ships at sea, made twice daily, are also available. To facilitate the transmission of the reports, they are put into a symbol, word, or figure code, depending upon the type of observation and whether the station making the report is on an airway, is an "off-airway" station, or a ship at sea.

Weather Bureau first-order stations at airway terminals, and a number of stations off the airways, are equipped to take observations of directions and velocities of upper-air winds. These are called "pilot-balloon observations." They are made at 6-hour intervals and are accomplished by means of a strong, but light, rubber balloon, which is inflated with the proper amount of hydrogen or helium to make it rise at a known rate of speed. This balloon is released and its progress in the upper air followed by means of a theodolite. The angles, representing the path of the balloon, are read at regular intervals until the balloon passes from sight, reaches a sufficient height for a satisfactory report, or bursts, as a result of the excess of internal over external pressure acting on the thin rubber walls of the balloon in the upper air. The readings thus obtained, when computed in connection with the rate of ascent, readily give the velocity and direction of the wind at the various desired altitudes. Such information is broadcast by radio to pilots. It is also transmitted by figure code on teletype and radio circuits, and, when charted for a number of stations, gives the pilot a picture of the winds he will encounter.

Upper-air observations are made also by means of airplanes at a number of stations in the United States, through cooperation of the Weather Bureau, and the War and Navy Departments. In most cases, the flights are made daily. The airplanes carry a self-registering instrument (aerometeorograph) which records the barometric pressure, temperature, and humidity throughout the flight. The records made by the instrument are coordinated with the conditions observed by the pilot, such as icing or precipitation, and the information obtained is transmitted in a code form by teletype and radio. This information is useful in identifying air masses, tracing their movements, and defining their boundaries, as well as indicating stability, water-vapor content of the air, and the likelihood of clouds or precipitation. These observations also give pilots informa-

tion regarding the height of the top of cloud layers and regions of icing conditions.

Observations of conditions in the upper air are made daily at a number of stations by means of radiosondes. The radiosonde is a lightweight instrument, with a radio transmitter, which, after being attached to a balloon and released, will transmit by radio a record of the barometric pressure, temperature, and relative humidity as it ascends. Such information is used in the same way as reports from airplane observations.

Upper-air observations, made by airline pilots in flight and received by the Weather Bureau stations are used in completing cross sections of the atmosphere and in perfecting analyses of meteorological conditions.

A system of teletype and radio circuits is provided by the Civil Aeronautics Authority for the rapid collection and distribution of weather information. Such a communication system is essential for an effective airway weather service. The weather observations are collected in sequences each hour, beginning with the first station on each circuit, and continuing station after station, in their proper order along the airway, until all reports of that circuit are collected. The reports of each circuit are then automatically relayed to such other circuits as require them.

Complete weather information is thus made available at every important airway terminal as soon as the sequence collections and relays have been completed, which is only a few minutes after the meteorological observations represented by the report have been made. The reports are broadcast by radio to pilots in the air, posted on Weather Bureau bulletin boards, entered on meteorological charts and maps, and disseminated by telephone systems as they are received, so that pilots and airline dispatchers have a constant knowledge of the latest developments in meteorological conditions. Stations off the airways report by telephone and telegraph, and these reports are collected at designated centers and relayed to teletype circuits for distribution to all stations where required.

Forecasting. Airway forecasters are on duty 24 hours a day at the general supervising stations, which are also forecast centers for their respective districts. At these stations airway forecasts are made every 5 hours for periods of 8 hours in advance for all airways and all terminals within the district. Such forecasts include ceiling

heights, visibility, sky conditions, precipitation, fog, smoke, haze, icing, thunderstorms, squalls, and other conditions expected to occur over the airways or at the terminal within the district during the period of the forecast. Special forecasts are issued when conditions change rapidly. In some instances, forecasts for a period longer than 8 hours in advance are made, when required, for long cross-country flights.

The professional meteorologist at a forecast center has much more information than the navigator or pilot flying over strange, or

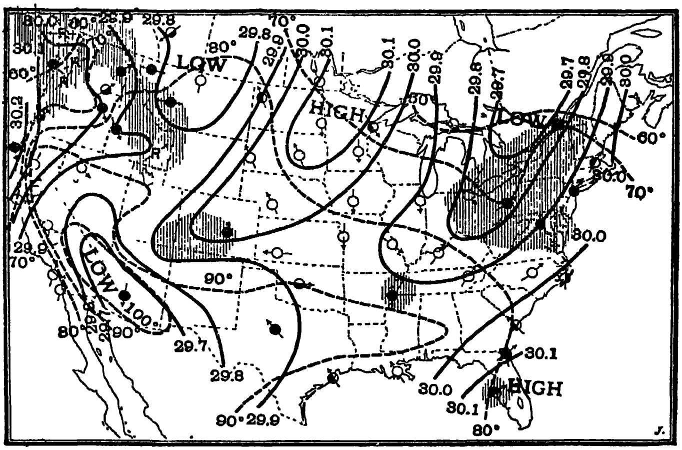


FIG. 81. A Weather Map Showing a Low Pressure Area Moving from Canada into Montana

enemy, territory. The navigator may have little more information than the reading of his instruments on the plane, or ship, and the cloud, wind, and weather conditions as he can see them. The forecaster has reports received every few hours from stations all over the country. The information includes, not only surface observations, but information received from airplane, radiosonde, and pilot-balloon observations.

The forecaster must know how to transfer this information to the map, to give him a general picture of the weather conditions over a large area, and he must know how to analyze and interpret this picture. To interpret the map correctly, the forecaster must understand the characteristics of the various air masses over the region,

and the formation, development, and travel of the cyclonic storms prevalent over that region.

Making Weather Maps. The information collected by means of radio, teletype, and telephone is used in the preparation of maps every 6 hours. In order to enter complete data on the maps, weather codes and symbols are used to conserve space. For the chief stations, the information entered includes wind force and wind direction at the time of reading, and the same for the highest wind in the last 6 hours; visibility, state of weather, ceiling, thunderstorm, if present; types of clouds and per cent of sky covered; the temperature and the dew point; barometric pressure and direction and amount of pressure change; time and amount of precipitation. The data are placed around the station circles on the map.

On the airway maps the barometric pressure, reduced to sea level, is recorded in millibars[1] rather than inches. *Isobars,* lines of equal pressure, are drawn with a black lead pencil for every two, three, or four millibars, according to the scale of the map used. At some stations the isobars are drawn also in inches of mercury.

In addition to the isobars, isotherms, lines of equal temperature, are drawn for 10° intervals. These are drawn lightly in blue at the forecast centers, but are not usually drawn at the airport offices.

The *fronts* are the lines which are drawn between air masses of different temperature or density. They are called warm fronts when warm air is replacing cold air at the ground, and cold fronts when cold air is displacing warm air at the ground. The fronts will be referred to again in the paragraphs on air masses. Heavy blue solid lines are used for cold fronts, and red for warm fronts. Stationary fronts are shown by continuous single lines composed of alternating red and blue segments.

An area of continuous *precipitation* is denoted by continuous green shading. An area with intermittent precipitation is denoted by hatching. Showery precipitation and drizzling precipitation are denoted by special symbols.

Air Masses. An air mass is a large portion of the Earth's atmosphere that approximates horizontal homogeneity. The formation of an air mass is usually the result of the stagnation of a large portion of the Earth's atmosphere over some rather uniform surface of either land or water for a period sufficiently long to enable its prop-

[1] 1000 millibars is equal to a pressure of 29.53 inches of mercury.

erties to reach equilibrium with respect to the surface beneath. At present, nine distinct air masses that frequent North America and the adjacent oceans are known to exist. The Polar Pacific, Tropical Gulf, and Polar Continental air masses are among those that appear in the United States during the entire year. Some of the others have only a seasonal occurrence.

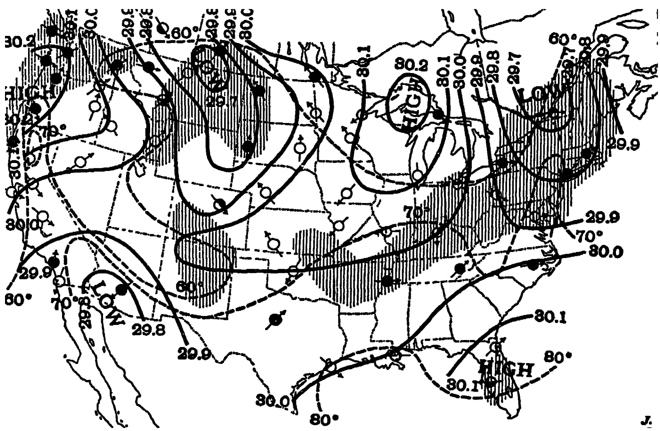


FIG. 82. The Storm in Fig. 81 a Day Later. Note precipitation over Montana

The region where an air mass acquires its characteristics is called a source region. These areas must be of rather uniform character, both as to temperature and as to type of surface, such as the North Pacific Ocean, North Central Canada, and the Gulf of Mexico. The source must be a region where air movements are rather sluggish in order to give the overlying air sufficient time to absorb its properties from the surface. It must be an anticyclone, or high pressure area, because the air moves slowly and often remains in one place for a considerable period of time in a high pressure area. A cyclone is never a source region because it moves too fast, is formed by two or more different air masses, and travels over areas having different qualities.

Sooner or later, the air masses are carried from their source regions by the general circulation of the atmosphere. This movement carries a Polar Continental air mass from North Central Canada down into the United States. In the middle latitudes some

modification of the initial properties of the air mass takes place as a result of the changes in temperature and type of surface over which it is passing. However, these new surfaces do not ordinarily cause abrupt changes within the air masses, and the air masses may still be classified as entities having definite characteristics.

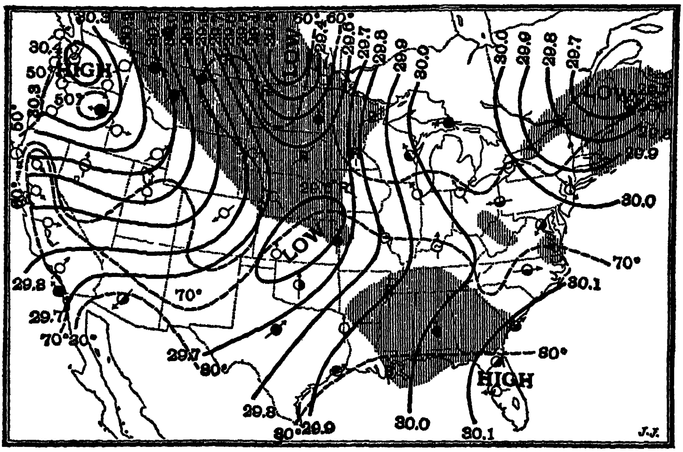
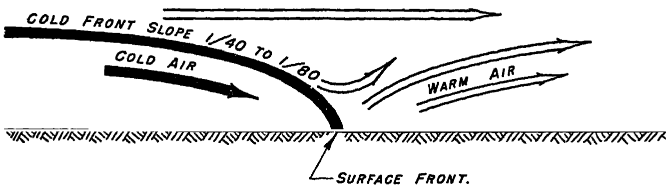


FIG. 83. The Storm of Fig. 81 on the Third Day. Note that precipitation has extended into Nebraska

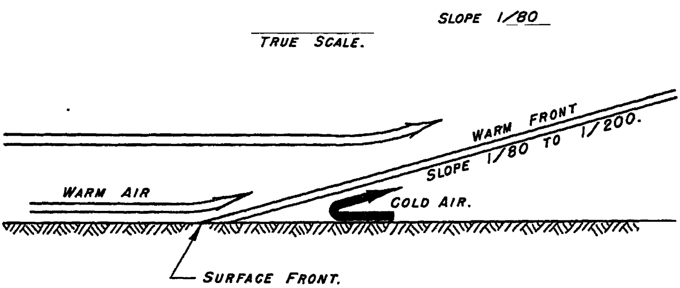
Warm air masses moving over colder ground exhibit different physical characteristics from cold air masses moving over warmer ground. Also, warm air masses tend to overrun cold air masses, and cold air masses tend to underrun warm air masses. Overrunning and underrunning are two great factors that influence the weather, especially in relatively flat areas. Therefore, it is essential that the forecaster keep in mind whether the air in a region is colder or warmer than the underlying surface of the Earth; whether there is overrunning or underrunning, and which air masses are doing it.

It is obvious that air masses originating in polar regions are materially different in structure from those attaining their initial characteristics over tropical latitudes. In the course of their migration over the Earth's surface, dissimilar air mass types may be brought together. Instead of simply mixing, a rather definite boundary called a *front* or "surface of discontinuity" arises between them. This surface may be considered impenetrable by the air masses on either

side as long as a marked discontinuity exists. Air is a fluid, and the two dissimilar air masses are fluids of different densities, with the cold, dry, polar air masses being heavier than the warm tropical masses. The cold heavy masses will tend to underrun the warmer types.



COLD FRONT (VERTICAL SECTION)



WARM FRONT (VERTICAL SECTION).

FIG. 84. Idealized Sections Showing the Meeting of Warm and Cold Air Masses

As an illustration of the formation of a discontinuity surface between two dissimilar fluids, consider the case of oil and water confined in a vessel. If the fluids are allowed to reach the equilibrium state, the water will underlie the oil, which is the lighter of the two. A definite boundary surface will be visible between them which, if the fluids are not in motion, will take a horizontal position. This is analogous to the case of a boundary surface separating polar and equatorial air currents. However, in the atmosphere, the fluids involved are ordinarily in motion, a condition which brings

into play forces which cause the discontinuity surface to become a sloping one. The front assumes a position such that the cold, heavy air underruns the warm, light air in the form of a very flat wedge. In fact, the slope of any atmospheric discontinuity surface is roughly of the order of 1 to 100. Since a weather map represents a plane surface, the sloping fronts or atmospheric discontinuity surfaces in the sea level plane represented by the weather map must intersect in a line. These atmospheric discontinuity surfaces form the boundaries of the air masses, and when an air mass starts to move, its forward portion is bounded by a front named from that air mass. The frontal boundary of a migratory cold air mass is called a *cold front*; the frontal boundary of a warm air mass is called a *warm front*. Therefore, a warm front exists where warmer air is replacing colder air, and a cold front exists where colder air is replacing warmer air, providing that the two air masses involved in each case are separated by a substantial discontinuity surface. (See Fig. 84.)

Motions of Cyclonic Storms. You read in the chapter on Weather that in the United States the weather changes are dependent primarily on the *extra-tropical cyclones*, which move across the country in a general way from west to east. These storms are formed at the boundary between two dissimilar air masses, and it is important that the forecaster understand the process of formation, the usual life history, and the usual movements.

The life history of a cyclone is shown in Fig. 85, parts *A-F*. Part *A* shows the front extending along a line that is approximately straight. Detailed analyses of surface fronts have shown that they present many minor irregularities. Part *B* shows the development of one of these irregularities into a small wave, with an associated precipitation area. It also shows that this precipitation area is due to the development of a component in the warm air perpendicular to the front. In part *C*, a wave development has progressed to the point where there is a definite cyclonic circulation, a warm sector, a well-defined crest with warm and cold fronts on either side, and the typical precipitation areas. Because of the more rapid movement of the cold front, part *D* shows a narrowed warm sector and the approach of the cold front to the warm front. In part *E*, an occlusion process is taking place, the cyclone has reached its maximum development, and the warm sector is being rapidly pinched off. In

part *F*, the warm sector has been eliminated, the cyclone is in its dying stages, and it is represented only by a whirl of cold air that is rapidly dissipating in strength.

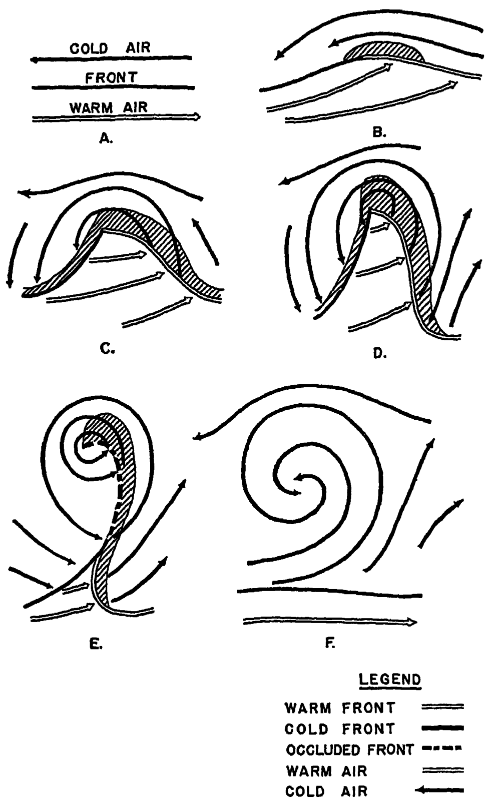


FIG. 85. The Life History of a Cyclone

A simplified weather map showing only the isobars, precipitation areas, and fronts, and two vertical sections of an ideal cyclone are shown in Fig. 86. The shaded portions show the precipitation areas, the largest of which is ahead of the warm front, but there is also a narrow band of precipitation along the cold front. The passage of the warm front is preceded by a large number of clouds of various types and quite a period of precipitation. After the passage of the warm front, there is an area where the sky is relatively clear

and the air is warm. As the cold front approaches, clouds again begin to appear, there is a brief period of heavy precipitation during and shortly after the passage of the cold front, and then the air is cold. Frequently, showers occur for a time after the passage of the cold front.

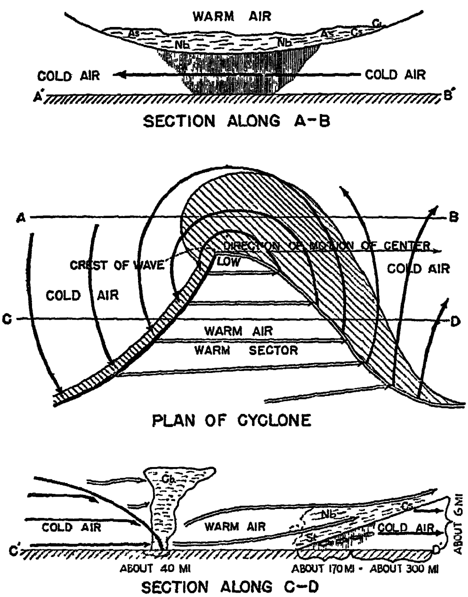


FIG. 86. Idealized Map and Sections of a Cyclonic Storm

The upper part of Fig. 86 represents a vertical section through the atmosphere a short distance north of the cyclonic center. It shows cold air everywhere at the surface, with the warm air and cloud systems aloft, and with the rain falling through the cold air from the clouds in the warm air. The lower part shows a vertical section some distance south of the center with typical sectional appearances of the warm and cold fronts.

Within the belt of the prevailing westerlies, the general movement of the cyclonic storms is from west to east. Weather maps of a cyclone which moved into the United States from Canada are shown in Figs. 81, 82 and 83.

In the chapter on weather you read that one of the regions in

which tropical cyclones occur is the West Indies. Many of these tropical cyclones, or hurricanes, move from the West Indies on to the coast of Texas or Florida. Occasionally, those which strike Florida move up the Atlantic coast, although after striking land

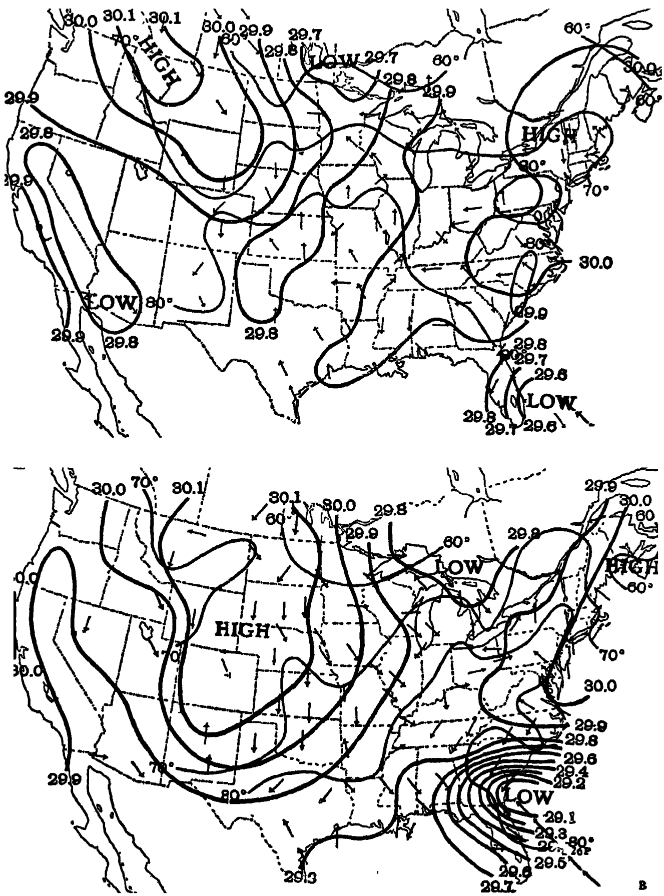


FIG. 87. Tropical Cyclone Moving Up Atlantic Coast, First Two Days

their force is diminished. In Figs. 86 and 87, the progress of a tropical hurricane from off the coast of Florida to Maine and southern Canada is shown.

You have read that the *tornado* is smaller and more violent than

the cyclonic storms just discussed. Because of its small size and short duration, the tornado cannot be forecast successfully. Tornadoes are associated with thunderstorms, however, and conditions which

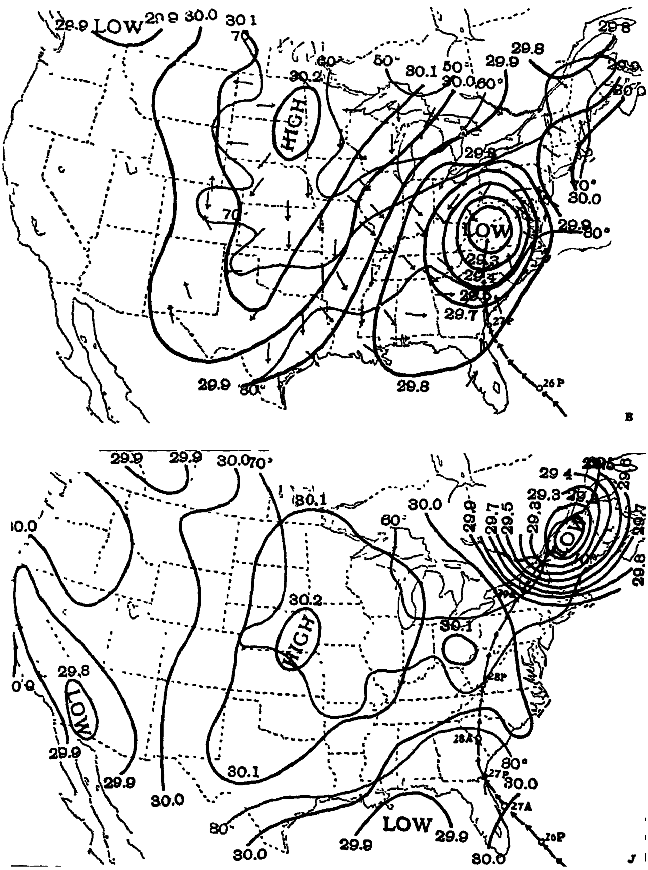


FIG. 88. Third and Fourth Day of Cyclone shown in Fig. 87

favor severe thunderstorms with large hailstones are, in general, favorable for tornadoes. They are more frequent in the spring and early summer months, in the middle western states, and along cold fronts. The weather forecaster knows this, but he cannot predict tornadoes, only thunderstorms.

Exercises

1. What are the various divisions and departments of the U. S. Weather Bureau? What are their services?
2. What observations does the average cooperative observer make?
3. What is the importance of the Marine Meteorological Service?
4. At what interval are weather observations made by observers at most airports?
5. What weather elements are included in the regular observations at airway stations?
6. What information is included in weather reports which are collected for airway forecasts?
7. What does the pilot, or navigator, when flying over enemy territory, have to rely upon to tell him the weather conditions?
8. What information does the forecaster place on a weather map of the United States?
9. Define isobar, isotherm, and front.
10. How and where are air masses formed?
11. Name the three air masses most important in the United States.
12. Give the life history of the usual cyclonic storm.

☆ X ☆

Maps

A map is a conventional picture of an area of land, sea, or sky. Perhaps the maps most widely used are the road maps given away by the oil companies. They show the cultural features such as states, towns, parks, and roads, especially paved roads. They show also natural features, such as rivers and lakes, and sometimes mountains. As simple maps, most automobile drivers have on various occasions used sketches drawn by service station men, or by friends, to show the best automobile route from one town to another.

Map and Chart. The distinction usually made between "maps" and "charts" is that a chart is a representation of an area consisting chiefly of water; a map represents an area that is predominantly land. It is easy to see how this distinction arose in the days when there was no navigation over land, but a truer distinction is that charts are specially designed for use in navigation, whether at sea or in the air.

Charts are intended not only to furnish an accurate representation of an area, but also to serve as a suitable base for the plotting of a problem of navigation in order to arrive at an accurate solution. The safety of life and property demands the greatest care and accuracy in all details.

Maps have been used since the earliest civilizations, and explorers find that they are used in rather simple civilizations at the present time by people who are accustomed to traveling. For example, Arctic explorers have obtained considerable help from maps of the coast lines showing settlements, drawn by Eskimo people. Occasionally maps show not only the roads, but pictures of other features. One of the earliest such maps dates from about 1400 B.C. It shows not only roads, but also lakes with fish, and a canal with crocodiles and a bridge over the canal. This is somewhat similar to the modern

maps of a state which show for each large town some feature of interest or the chief products of that town.

Roman Maps. The maps of the Romans were primarily military road maps from which the army men could read the road, various towns or stations along the road, and the distance from one of the stations to another. The maps were not drawn to show the scale or the location of each town with respect to the others accurately. In this respect the Roman maps resembled modern railroad maps which show the railroad as a line going straight across the state, in spite of numerous curves, and show the stations spaced approximately at equal distances in spite of the fact that the distances may vary considerably. An adjoining table gives the correct distance in miles and there is no attempt to represent the distances correctly on the maps.

The Greeks made the first attempts at accurate mapping, so that the direction and distance of one place from another could be scaled directly from the map. They were the first to recognize that in mapping large areas of land or water, allowance must be made for the fact that the Earth is a sphere while the map is a plane. The astronomer Hipparchus developed stereographic projections as a method of representing a spherical area as a portion of the Earth more accurately on a plane figure such as a map. The astronomer Ptolemy, who lived about 150 A.D., made what is generally considered the first reasonably accurate map of the known world, using the projection developed by Hipparchus.

After the fall of Rome, and until about the time of Columbus, the science of map making along with much other human knowledge was forgotten. The scholar Gerhard Kremer, 1512-1594, better known as Mercator, invented the projection which bears his name, and which probably is the one most widely used for maps of land, sea, and sky. In this projection the parallels of latitude are represented by horizontal straight lines and the meridians by parallel vertical lines. The distance apart of the parallels of latitude is increased as the latitude increases. The advantage of this projection to navigators is that the rhumb lines[1] become straight lines.

The Fundamental Meridian. For centuries there was consider-

[1] A rhumb line crosses all meridians of longitude at the same angle. A ship sailing without changing its compass direction follows a rhumb line. On the Mercator projection this is a straight line, but because of the convergence of the meridians at the poles, on the Earth it is a curve.

able disagreement among map makers as to what fundamental meridian should be used. Ptolemy had used the Canary Islands, the westernmost land known. In the sixteenth century some used one of the Cape Verde Islands, some followed Ptolemy in using the Canary Islands, and others used the Azores. Eventually, a papal decree brought agreement on the use of a meridian passing through Ferro (Hierro), the westernmost of the Canary Island group. The use of this meridian, meant that all of Europe, Asia, and Africa would be in the eastern or positive longitudes. Maps showing longitudes from Ferro were in use as late as 1870.

With the introduction of standard time in 1882, the nations of the World agreed generally on the meridian of Greenwich, the British National Observatory in London. With time counted from that meridian, longitudes also were counted from that meridian, and soon after that date practically all maps were drawn with the meridians counted from Greenwich.

In the days of Mercator and for more than 100 years after his time, mapping was left largely to individuals. It was necessary for the maker of maps to obtain the cost of collecting his information from the sale of his maps. In the 1700's France began an accurate mapping of that country at government expense. As the maps were made primarily for military purposes, the work was largely under the direction of the army engineers. Since that time nearly all the leading nations have mapped most of their territory accurately.

Triangulation. Accurate mapping includes two types of work, engineering and astronomical. The engineering work is as follows. Certain base lines are measured very accurately, usually with a tape and microscopic equipment. In Fig. 89, the base line is the heavy line between "East Base" and "West Base." From the two bases sights are made on two adjoining stations, Yuma No. 9 and Azimuth Station, and the angles measured accurately with a theodolite. This gives two triangles, in each of which two angles and the included side are known. The other sides of the triangles can be calculated, and also the diagonal of the quadrilateral, that is, the distance between the two stations. From Yuma No. 9 and Azimuth Station, sights can be made on two more distant stations, Pilot Knob and Yuma No. 10. Then the sides of the new triangles, and the distance from Pilot Knob to Yuma No. 10 can be calculated. By continuing

this process the engineers eventually have the longest distances, as from Gila to Yuma No. 11, with accuracy.

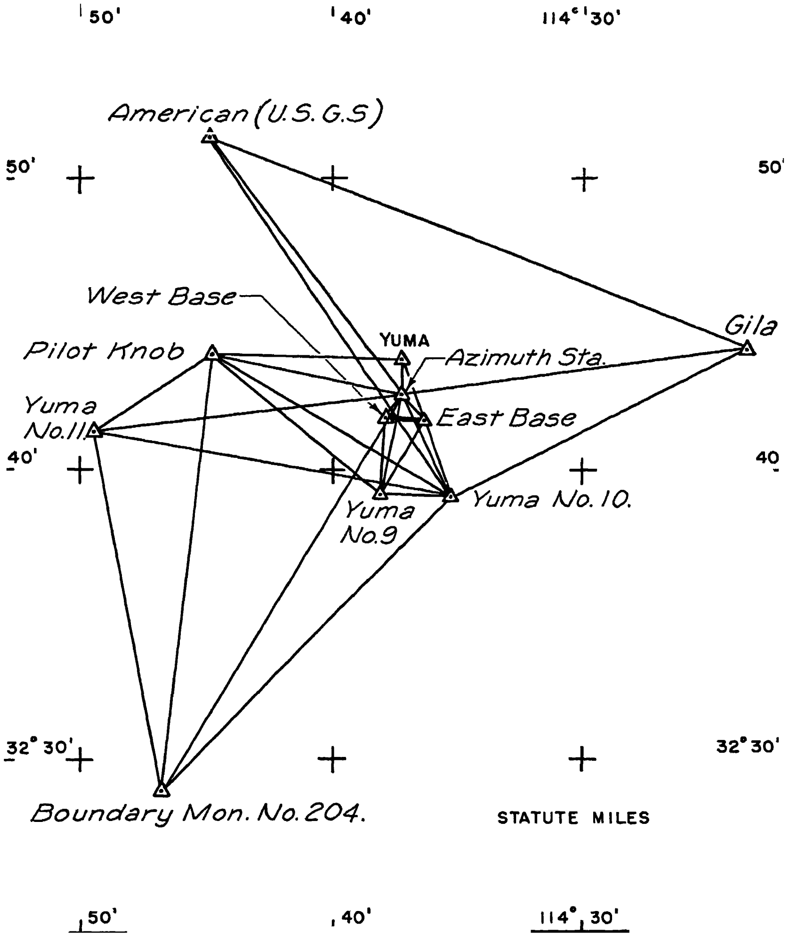


FIG. 89. Triangulation in Yuma and Vicinity

The astronomical work is the determination of accurate longitudes and latitudes for three or four of the stations. From these the scale of longitudes and the scale of latitudes can be marked on the map, and reasonably accurate values of the coordinates read off for any points.

Topographic Maps. In the first work, government maps showed only the location of the stations. There was no attempt to show the topography, or the relief, of the country. The French astronomer Laplace suggested in 1816 that the topography should be shown, and by 1850, the leading nations had undertaken that work. A considerable portion of the territory of each of the leading countries has been mapped on a relatively large scale to show the contour lines.

In the preparation of maps definite conventions have developed, evaluating the relative importance of features to be mapped and the emphasis to be given each. On aeronautical charts, items which would normally be included in any ordinary map are often omitted in order not to obscure details of greater importance to the navigator, while other features are sometimes exaggerated beyond topographic justification, because of their landmark value.

The aeronautical charts include more than 25,000 miles of airways equipped with beacon lights, radio ranges, teletype service, weather reporting stations, and other related features. Over such an extensive system it is clear that many changes must occur. New airways are being established and old routes rebuilt for more efficient operation, and aids are even being provided for the navigation of air routes across the oceans, and for the extension of routes into Alaska. Once the information on a chart has become obsolete, its further use is a definite hazard. The frequent correction of its charts, to show the changes in information as they occur, is a most important function of the Government, and is imperative for safety in all forms of air transportation.

Aeronautical Charts. An aeronautical chart, then, may be defined as a small-scale representation of a portion of the Earth and its culture, presenting to the trained eye a description of the charted region more nearly perfect than could be obtained from the pages of a book. It depicts the land marks and other information found of value by pilots long familiar with the region, and provides a base suitable for the solution of the problems of air navigation. Consequently, any time spent in learning to read and interpret its detailed information will be well repaid.

In charting the details of the terrain and the system of aids to navigation, many conventional symbols are employed. Some of these have been in use for many years, and their significance is

generally understood; others have been adopted more recently and are of more specialized use, and therefore, are not as well known. The following description of these symbols and their significance has been prepared as an aid to chart reading. It applies primarily to the sectional charts since the scale of that series permits the charting of fairly complete information. On the smaller scale charts many details must be omitted, but with few exceptions those that can be included are shown by the same symbols.

The features shown on these charts may be divided into two groups:

1. *Topographic information* necessary to a clear and accurate representation of the region.
2. *Aeronautical data* and information of interest chiefly for air navigation.

   The topographic features may in turn be subdivided into three groups:

   a. Water, including streams, lakes, canals, swamps, and other bodies of water.
   b. Culture, such as towns, cities, roads, railroads, and other works of man.
   c. Relief, including mountains, hills, valleys, and other inequalities of the land surface.

Water Features. These are represented on the aeronautical charts in blue, the smaller streams and canals by single blue lines, the larger streams and other bodies of water by blue tint within the solid blue lines outlining their extent.

Intermittent streams are shown by a series of long dashes separated by groups of three dots, suggesting the scattered pools into which the diminished streams sink during the dry season. Intermittent lakes and ponds are shown with broken shore line and cross ruling in blue. In some sections of the country the beds of dry lakes and ponds are conspicuous landmarks. Such features are indicated by brown dots within the broken "shore line" of blue.

Marsh areas are shown by horizontal blue lines with scattered groups of short vertical dashes suggesting the clumps of marsh grass common in such areas. Glaciers are indicated by blue shading, representing the form and the flow lines of the glacial area.

Cultural Features. These are generally indicated in black. Towns

with a population of less than 1,000 are indicated by a conventional black circle. Towns having a population between 1,000 and 5,000 are shown by a yellow square outlined by purple, while the actual shapes of larger cities are shown in yellow within a purple outline.

Railroads are represented by fairly heavy black lines with crossties at 5-mile intervals, electric railways (trolleys) by lighter black lines with crossties at 2½-mile intervals. Single-track railroads are shown with single crossties, while for railroads of two or more tracks the crossties are in pairs. Even if a railroad has been abandoned or torn up, the old roadbed is sometimes a prominent feature when viewed from the air. When this is the case it is indicated on the chart by a broken black line.

Tunnels are indicated not only because they serve as landmarks, but also because they are a source of potential danger. If a pilot is following a railroad through territory with which he is not familiar, and the railroad enters a tunnel, he may find himself suddenly deprived of the one landmark upon which he was relying, or even confronted by a mountainside, without sufficient space either to turn or to climb above it. This difficulty is seldom encountered in the case of highways, but any highway tunnels are shown by the same symbol.

Prominent highways are indicated by a heavy purple line, secondary highways by lighter lines in purple. The highway route number, centered within a shield, is shown at intervals along the principal Federal highways. In some states the main roads are air marked with the same numbers, as an aid to identification from the air. In a few instances, in sparsely settled country where there are few other landmarks, very poor roads are charted because of their unusual landmark value, and such roads are shown by a broken purple line (the conventional symbol for a trail).

"Prominent highways" and "secondary highways" must be understood as only relative terms. In some of the thinly settled western districts, roads are so few that practically all of them are shown; the most important through highway may be only a well-graded dirt or gravel road, yet it is so prominent in its own vicinity that it is charted with a heavy line. On the other hand, in the more thickly settled sections, there are so many roads that it is impossible even to include all the highly improved roads. The treatment of high-

ways, then, varies with the region under consideration, but in each case an attempt is made to delineate the distinctive road pattern as it would be seen from the air.

Race tracks are prominent landmarks, and whenever possible their characteristic oval shapes are indicated in black. In congested areas where the actual shape cannot be shown, the location is sometimes indicated by a heavy dot, and the words "Race track," or the letters "R. T." are printed in the nearest open space, with an arrow leading to the dot.

Lookout towers in the state and national forests are located on the highest ground in the vicinity and are usually quite prominent. In some cases they have been air marked with a number, and these numbers appear on the chart adjacent to the symbols in vertical black figures. Elevations of the ground at the towers are added in black italics. Forest ranger stations are shown by small symbols suggestive of the ranger station and its flag. A Coast Guard station is indicated by a small black "boat," accompanied by the number with which it has been marked for identification from the air. A quarry, or a mine, is represented by a symbol suggesting the pick and hammer of the miner. In addition to the foregoing, there are in many localities a number of unclassified distinctive landmarks which are of great assistance in identifying position. These are usually indicated on the sectional charts with a dot and descriptive note.

It should be understood that, even on the larger-scale charts, certain features must be exaggerated in size. For example, if a prominent highway is measured by the scale of statute miles on a sectional chart, the highway appears to be about an eighth of a mile, or 650 feet in width, but this exaggeration is necessary for the sake of clarity and emphasis. Again, in a narrow canyon it may be required to show a stream with a railroad on one side and a highway on the other. On the ground the three features may occupy a space no more than 75 feet in width, yet on the chart, showing the three symbols as close together as possible, they appear to occupy more than a third of a mile, or about 2,000 feet.

In the case of water features, a small lake 300 feet wide and 2,000 feet long may be an outstanding landmark; at the actual scale of the chart 300 feet would be reduced to a fine single line; it must

be exaggerated in width enough to show a small area of blue tint between two limiting shore lines of solid blue, and in length enough to preserve in a general way, at least, the shape of the lake. Whenever possible, symbols are centered on their true locations and exaggerated only as much as may be essential to a clear representation.

Relief. This is shown by contour lines in brown, and is emphasized by a series of gradient tints ranging from green at sea level to a dark brown about 9,000 feet. On a few charts in the west, extensive areas below sea level are indicated by a faint purple tint.

Some prominent peaks, or steep cliffs, are also accentuated by hatching, or shading, with the elevations in black italic figures.

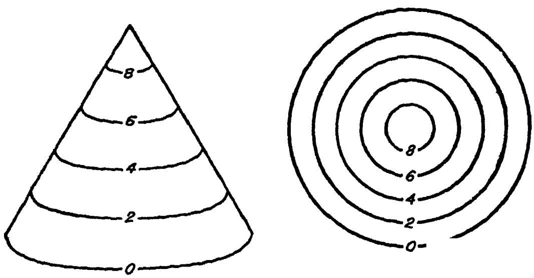


FIG. 90. Illustration of Contour Intervals

Many other critical elevations—mountain passes and high points—are shown on the charts with a dot to designate the location. The elevations of a number of cities and towns are also shown.

To clear up any confusion about contours, on a semicircular piece of paper draw a series of semicircles at intervals of about 2 inches. Now roll the paper into an ordinary "dunce cap," and pin it so it will not come undone. It will appear as at the left of Fig. 90, with the horizontal lines representing contours having successive differences in elevation of a little less than 2 inches.

If we set the dunce cap on the floor and look straight down upon it (which is the way the Earth's surface is represented on a chart), the system of "contours" will appear as at the right of the same figure.

Contour Maps. A contour represents an imaginary line on the ground every point of which is at the same height above sea level. The varied curves of the contour show the ridges, valleys, canyons,

bluffs, and other details. With a little practice, one may read from the contours not only the elevations but also the shape of the terrain as easily as from a relief map and much more accurately.

Any contour is the intersection of an imaginary horizontal plane with the surface of the terrain. To illustrate, Fig. 91 represents a

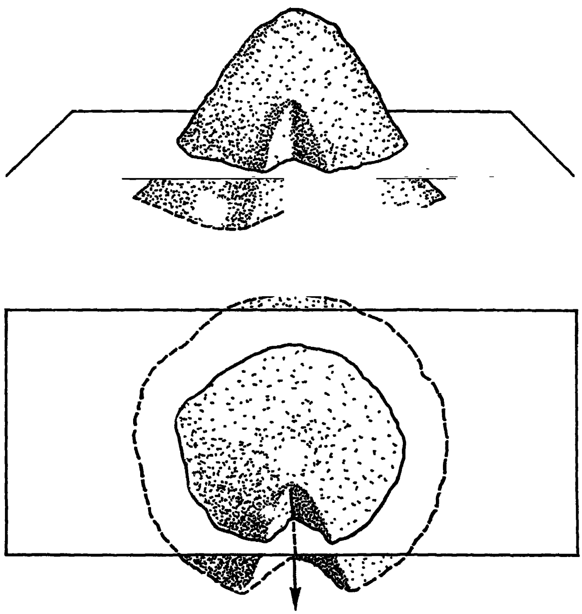


FIG. 91. Contour on a Pile of Sand

pile of sand from the nearer side of which sand has been carried away until a "valley" has been formed. The top of the sand pile is five feet above the pavement, and an imaginary plane is passed through the pile at a height of two feet. In the lower part of the figure is shown the "contour" or the trace of the intersection of the plane with the sand. The trace of the lower edge of the pile of sand on the pavement may be considered as the "shore line" or the line of zero altitude.

If it were raining, water would flow down the "valley" in the direction indicated by the arrow, which may be considered as a "stream." Thus we see that when contours cross a stream, they bend toward the source of the stream which is, of course, on higher

ground; conversely, when crossing a ridge, the contours bend away from the higher ground.

One way of visualizing more readily the significance of the contours is to think of them as successive shore lines if the sea should

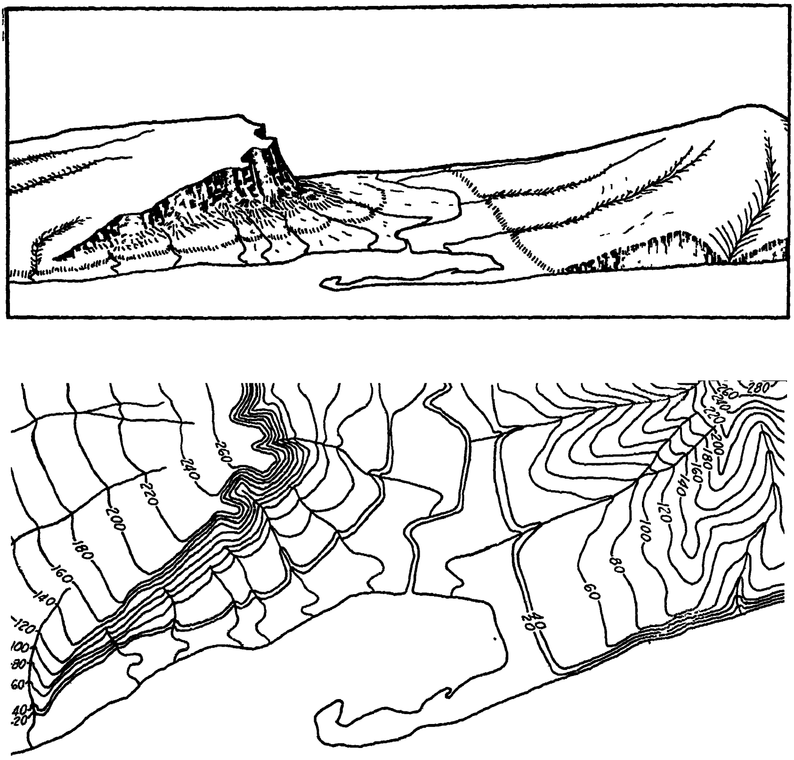


FIG. 92. An Irregular Land Surface and Its Corresponding Contour Map

rise to the levels indicated by the respective contours. The line of the seacoast itself is a contour, every point thereon having the same altitude (zero) with respect to mean high water. Valleys sloping down toward the shore line are represented by a curve or indentation landward. Ridges result in a curve seaward. Now if the sea should rise 1,000 feet, the 1,000-foot contour would become the shore line; valleys would still be indicated by a curve toward the

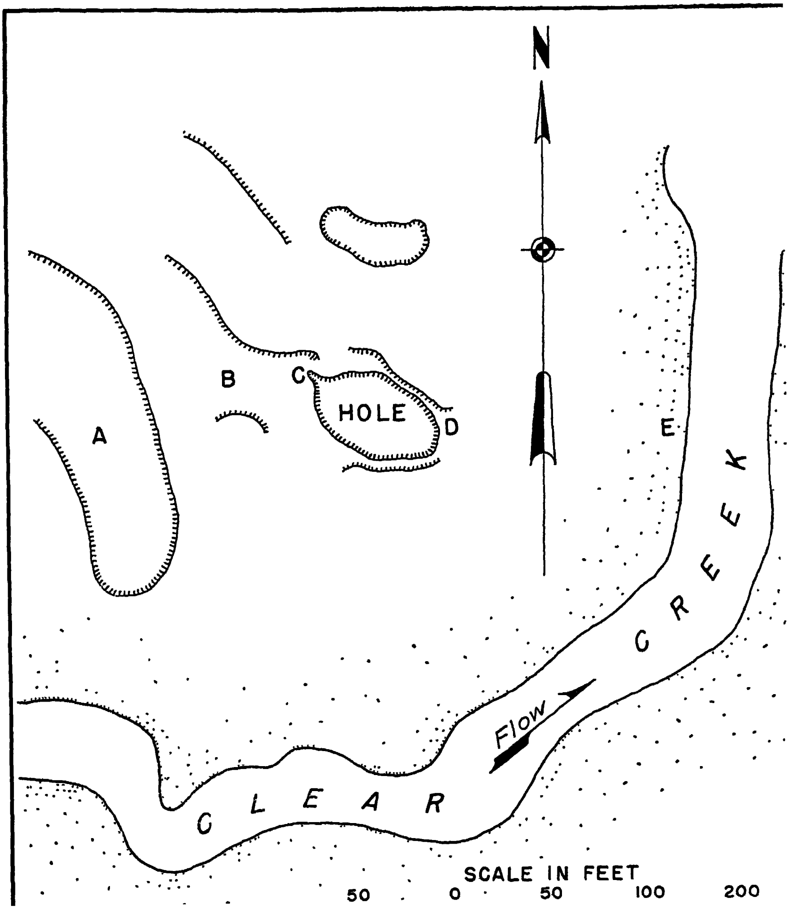


FIG. 93. The Tiffin Swirl Pit. A contour map of this "Hole" is shown in Fig. 94

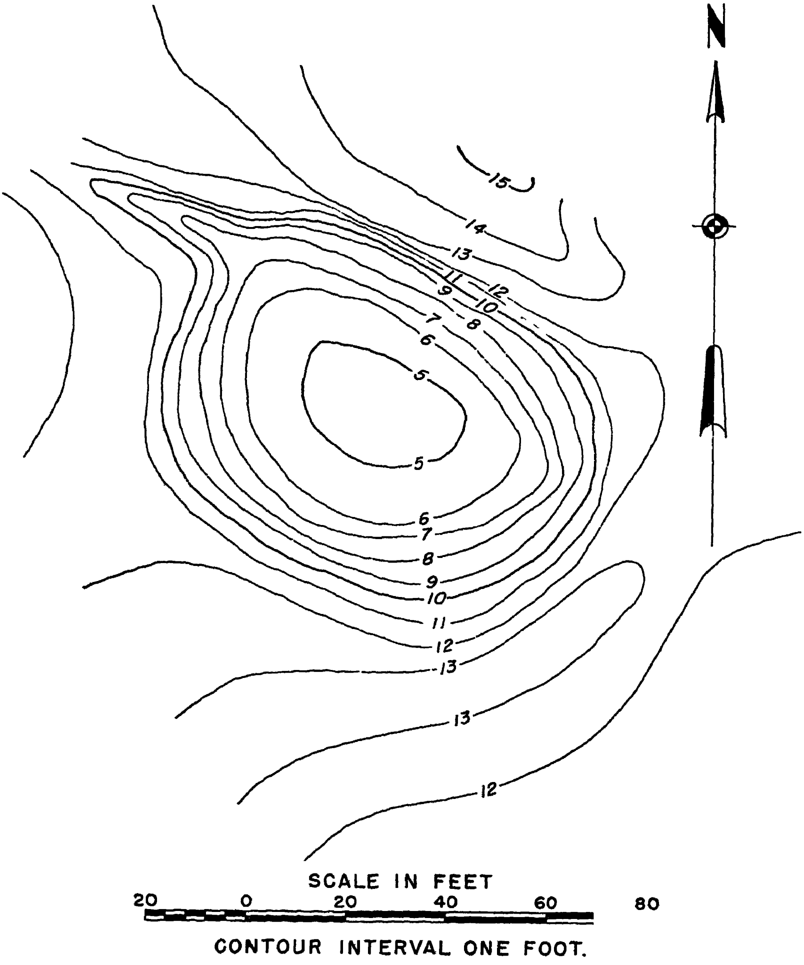


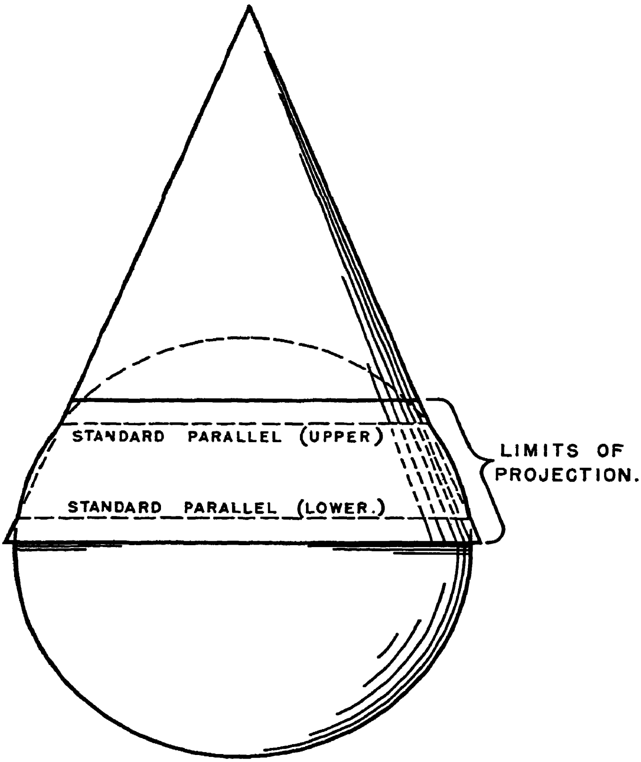
Fig. 94. A Contour Map of the Tiffin Swirl Pit

higher ground (which would now be called landward), and ridges would be indicated by a curve toward the lower ground (seaward). If a cliff should rise almost vertically above the shore line for 1,000 feet, the 1,000-foot contour would appear on the chart very close to the shore. When the terrain slopes gently upward from the coast, the 1,000-foot contour is a considerable distance inland. Thus, contour lines that are far apart on the chart indicate a gentle slope, while lines that are close together indicate a steep slope; contours that run together indicate a cliff.

The manner in which contours express altitude, form, and degree of slope is shown in Fig. 92. The sketch in the upper part of the figure represents a river valley that lies between two hills. In the foreground is the sea, with a bay that is partly enclosed by a hooked sand bar. On each side of the valley is a terrace into which small streams have cut narrow gullies. The hill on the right has a rounded summit and gently sloping spurs separated by ravines. The spurs are cut off sharply at their lower ends by a sea cliff. The hill at the left terminates abruptly at the valley in a steep and almost vertical bluff, from which it slopes gradually away and forms an inclined tableland that is traversed by a few shallow gullies. In the lower part of the figure, each of these features is represented directly beneath its position in the sketch by contour lines. The contours represent successive differences in elevation of 20 feet—that is, the "contour interval" is 20 feet.

As another illustration of the use of contour lines, Fig. 93 shows a "swirl pit" in the bottom land of a creek. A contour map on a larger scale (see Fig. 94) shows the details of the pit.

Land Maps and Star Maps. From the observer's point of view, there is a fundamental difference between maps of the Earth and maps of the sky. Maps of the Earth are drawn as though one were above and looking down on the area. The custom is to place north at the top, which places east to the right. For star maps, the observer is below and looking up, instead of looking down. A map of the northern sky should have the northern horizon down, east to the right and west to the left. A map of the southern sky should have the southern horizon down, west to the right and east to the left. To show the constellation figures as they appear, the directions must be reversed on the star map as compared with those on a map of land or water.



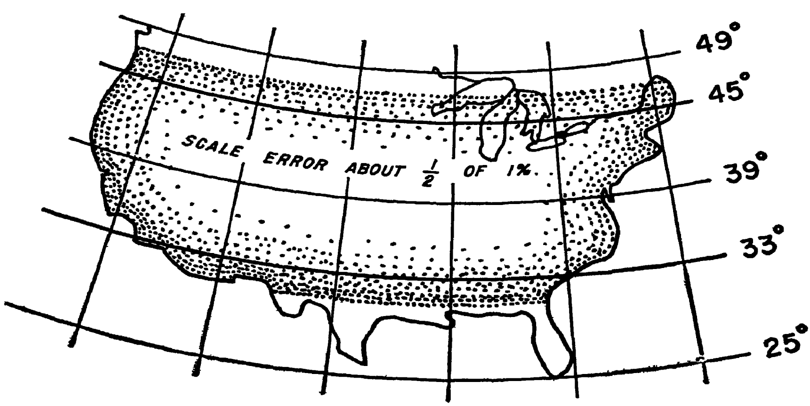


FIG. 95. The Lambert Conformal Projection

Map Projections. For accurate mapping, coordinate lines are essential. As you have read, longitude and latitude are used for points on the surface of the Earth, and right ascension and declination for the stars. A fundamental problem of map making is the calculation of the relation between the meridians of longitude and the parallels of latitude on the surface of the Earth, and the lines representing them on the map. For star maps the relation is between the hour circles and declination circles, and the lines representing them on the map. The methods of representation are called *projections*, and the following are among the more common.

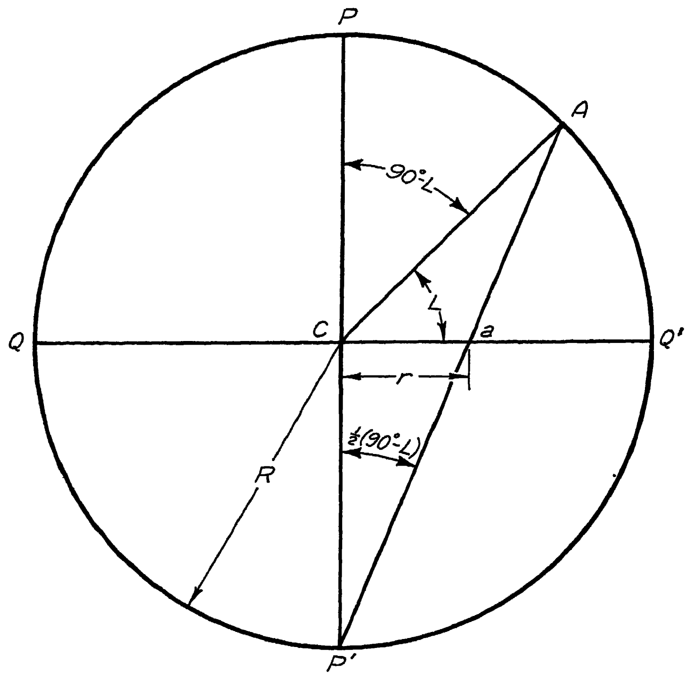
A map made on the *Mercator* projection has all meridians of longitude represented by parallel vertical lines and all parallels of latitude shown as parallel horizontal lines. Thus the straight lines representing meridians and parallels all cross each other at right angles. It is used extensively in marine navigation and in air navigation when the airplane carries a navigator as a member of the crew. Most of the Hydrographic Office charts for the U. S. Navy and the U. S. Coast and Geodetic Survey maps are constructed on this projection.

In the *Lambert conformal* projection the meridians of the Earth are represented by straight lines converging toward a common point outside the borders of the chart, and the parallels, by curved lines which are sections of concentric circles whose common center is at the point of intersection of the meridians. Meridians and parallels intersect at right angles. Fig. 95 shows the principle of this projection, which is from a spherical to a conical surface. The conical surface can then be laid out flat making a plane surface. The figure shows, also, a map of the United States on this projection. Distances can be measured directly by means of the graphic scales printed on the border. If the entire United States is shown on a single chart, as in the figure, the maximum scale error for nearly 90 per cent of the chart is about ½ of 1 per cent—an error quite negligible in practice.

In the *gnomonic* projection the meridians are represented as straight lines, and the parallels of latitude are shown as curved lines with the exception of the equator, which is a straight line. If the projection is centered on the equator, the meridians are parallel straight lines, otherwise they are converging lines. Charts made on this projection are sometimes called "great circle charts" because a

straight line drawn on such a chart will indicate a great circle, which is the shortest distance between points on a sphere. The fact that it shows the shortest route as a straight line makes it useful, and some Hydrographic Office charts are constructed on this projection.

The *stereographic* projection, if centered on the pole, represents the meridians as straight lines intersecting at the pole and the



$r = R \tan \frac{1}{2}(90° - L)$

FIG. 96. The Stereographic Projection

parallels of latitude as circles centered on the pole. The stereographic projection has the property that all circles on the sphere are projected into circles (or straight lines) on the map.

Many of the maps of the circumpolar regions of the World are constructed on the stereographic projection centered on the pole. The series of constellation maps showing the northern and the southern sky (Map 1 to Map 12 inclusive) are constructed on the

stereographic projection. For the northern sky, the mathematical point of view is the south point of the horizon, and for the southern sky the mathematical point of view is the northern point of the horizon.

To illustrate the mathematics of a simple problem of map projection, let us calculate the radius r of the circle to represent the parallel of latitude, for latitude L on a stereographic projection centered on the pole. In Fig. 96 the point of vision of the eye is at P', and each point, A, on the sphere is projected into the corresponding point, a, on the plane of the equator, QQ'.

$$ACQ' = \text{Latitude} = L$$
$$AP'C = \tfrac{1}{2}\,(90° - L)$$
and
$$r = R \tan \tfrac{1}{2}\,(90° - L)$$

By assuming the proper value for R, a convenient scale for the map can be obtained. The radius, r, can be calculated for as many values of the latitude, L, as is desired. In this projection angles are preserved, and as many meridians as desired can be drawn intersecting at the pole, P.

Exercises

1. What is the technical distinction between "map" and "chart"?
2. Who were the first people to allow for the Earth's true shape in their map making?
3. What is meant by "Longitude from Ferro", seen on maps of 75 or more years ago?
4. What is the fundamental meridian for modern maps?
5. In the triangle ABC, side AB is 14.32 miles, angle A is 78° 41′, and angle B is 67° 39′. Find the distances AC and BC.
6. Describe the steps in measuring relatively long distances by triangulation.
7. What is a topographic map? What information does it contain?
8. How is relief on a map shown? Define "contour."
9. Name and explain the common types of map projection.
10. Using 5 units as the radius of the Earth, calculate the radii for

a stereographic projection of the Earth to 40° south latitude. Calculate for each 10° of latitude.

11. Using the data from problem 10 draw a map including the meridians of longitude for every 10° and locate New York City, London, Berlin, Moscow, Tokyo, and San Francisco on it.
12. Draw Greenland and Australia on the map from problem 11, by scaling the approximate longitude and latitude of various points from an atlas. Notice how much too large one of these two is on your map.

☆ XI ☆

Time

The subject of *time* is one of the most important in the study of astronomy. Time is so important in everyday life that tests have shown it to be one of the most common words in the English language. It enters into every operation for the astronomical determination of a ship's position.

Several terms defined in the chapter on the celestial sphere will be used in the discussion of time. In addition, the terms "hour circle" and "hour angle" will be defined, as they will be used in the discussion.

Hour circles are great circles passing through the celestial poles, and the *hour angle* of an object on the celestial sphere is the angle at the celestial pole between the meridian and the hour circle passing through the object. The hour angle is counted positive toward the west.

In Fig. 97 let P be the pole of the celestial sphere, of which VMQ is the equator, PQ the celestial meridian, and PM, PS, and PV, the hour circles of the mean Sun, a star, and the vernal equinox.

Then QPM, or its arc QM, is the hour angle of the mean Sun; QPS, or QS, the hour angle of the star; QPV, or QV, the hour angle of the vernal equinox, or the sidereal time; VPQ, or VQ, the right ascension of the meridian; VPS, or VS, the right ascension of the star; and VPM, or VM, the right ascension of the mean Sun.

The instant at which any point of the celestial sphere is on the meridian of an observer is the time of transit, or meridian passage, of that point. When the passage is over that half of the meridian which contains the zenith, it is designated as superior or upper transit; when over the half containing the nadir, as inferior or lower transit.

Three different kinds of time are employed in astronomy—apparent solar time, mean time, and sidereal time. These depend upon the hour angle of the points to which they respectively refer. The point of reference for apparent solar time is the center of the Sun; for mean time, the center of an imaginary mean Sun; and for sidereal time, the vernal equinox.

Apparent solar time is the hour angle of the center of the Sun. In the *American Nautical Almanac*, an apparent solar day at any place is the interval of time between two successive lower transits of the center of the Sun over the meridian of that place, and the time of day is the hour angle of the center of the Sun, plus 12 hours. Apparent noon is the time when the latitude can be most readily determined. The ordinary method of determining the longitude by the Sun involves first a calculation to deduce the apparent time.

You have read in the chapter on motions of the Earth that the Sun is sometimes more than 15 minutes ahead of or behind the position it would have if all days were of uniform length. The Earth moves most rapidly in its orbit when nearest the Sun, which is early in January. This tends to make the days longer at that time. Since the plane of the equator does not coincide with the plane of the ecliptic, the Sun is higher in the sky in Summer than in Winter. This tends to make the days shorter near the equinoxes when the Sun has the greatest motion up or down in the sky. Since it would be inconvenient to run clocks on this variable time, astronomers compute the amount the Sun is ahead of or behind the average, and speak of an imaginary *mean Sun* in this corrected position. Thus, *mean solar time* is the hour angle of the mean Sun.

The difference between mean and apparent time is called the equation of time. This is tabulated for each two hours of Greenwich time in the *American Nautical Almanac*. It is marked minus when the Sun is slow, and plus when the Sun is fast. Mean time can be obtained by observing the hour angle of the sun, and applying the equation of time.

The *civil day* commences at midnight and comprises the 24 hours until the following midnight. In the *American Nautical Almanac*, the hours are counted from zero to 24, but as ordinarily used in civil life, the hours are counted from noon to midnight, thus

dividing the day into two periods of 12 hours each in which the hours are respectively marked a.m. (ante meridian) and p.m. (post meridian).

The *astronomical day* commences at noon of the civil day of the same date. It comprises 24 hours, reckoned from zero to 24, from noon of one day to noon of the next. Astronomical time (apparent or mean) is the hour angle of the Sun (true or mean) measured to the westward from the time of its upper transit on one day to the same instant on the next.

The civil day, therefore, begins 12 hours before the astronomical day, and a clear understanding of this fact is all that is required for interconverting these times. For example, January 9, 2:00 a.m., civil time, is January 8, 14^h astronomical time. January 9, 2^h, astronomical time is January 9, 2:00 p.m., civil time.

Astronomers are not the only people working at the hour of midnight, who make the change of date at some more convenient hour. In the large cities the traction companies are quite busy from twelve o'clock until after one a.m. taking the theater crowds home. In issuing transfers, it is customary for them to use transfers of the same date after midnight as before. A transfer of date 12:45 a.m., January 10, would then actually be good only at 12:45 a.m., January 11, civil time. Factories working on 24-hour shifts often find it more convenient to make the change of day at some other hour than midnight. Hospitals and police stations, where the legal date is a matter of importance are careful, however, to make the change of date exactly at midnight.

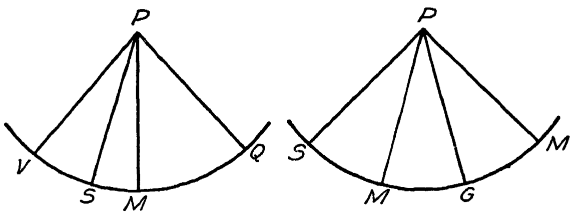
Sidereal time is the hour angle of the *vernal equinox*, or the right ascension of the observer's meridian. In practice it may be determined by observing stars as they pass the meridian, at which time a sidereal clock should read the right ascension of the star; or it may be determined by observing the position of a star not on the meridian and computing its hour angle. The sidereal time is equal to the right ascension of the star plus its hour angle.

A *sidereal day* is the interval of time between two successive upper transits of the vernal equinox across the meridian. Sidereal noon is the instant at which the hour circle of the vernal equinox coincides with the meridian. In order to convert sidereal time into mean solar time and vice versa, the *American Nautical Almanac* tabulates for Greenwich the "Sidereal Time of 0^h Civil Time" each

day. This is simply the sidereal time of Greenwich mean midnight.

The hour angle of the true Sun at any meridian when increased by 12 hours is the local apparent civil time; that of the mean Sun, when increased by 12 hours, the local civil time; that of the vernal equinox, the local sidereal time.

In comparing corresponding times of *different meridians* the most easterly meridian may be distinguished as that at which the time is greatest or latest.



a b

FIG. 97. Hour Circles and Hour Angles

In Fig. 97b let PM and PM' represent the celestial meridians of two places, PS the hour circle through the Sun, and PG the Greenwich meridian; let

$T_G =$ the Greenwich time $= GPS + 12^h$;

$T_M =$ the corresponding local time at all places on the meridian $PM = MPS + 12^h$;

$T_M' =$ the corresponding local time at all places on the meridian $PM' = M'PS + 12^h$;

$Lo =$ west longitude of meridian $PM = GPM$;

$Lo' =$ east longitude of meridian $PM' = GPM'$.

If west longitudes and hour angles be reckoned as positive, and east longitudes and hour angles as negative, we have:

$Lo = T_G - T_M$; $Lo' = T_G - T_M'$.

Therefore,

$Lo - Lo' = T_M' - T_M$.

Thus it may be seen that the difference of longitude between two places equals the difference of their local times. This relation holds for any two meridians whatsoever.

Both local and Greenwich times in the above formula must be

reckoned westward, always from their respective meridians and from 0^h to 24^h. The formula $Lo = T_G - T_M$ is true for any kind of time, solar or sidereal; or, in general terms, T_G and T_M are the hour angles of any point of the sphere at the two meridians whose difference of longitudes is *Lo.* In the figure, *S* may be the Sun (true or mean), or the vernal equinox.

Standard time is the local civil time of meridians, known as standard meridians, located 15° of longitude apart, commencing with the meridian of Greenwich as the initial meridian. The time of a standard meridian is used for the convenience of railways and affairs of everyday life in a belt extending, as nearly as practicable, 7½° each side of the standard meridian. *Daylight,* or *war,* time is one hour faster than standard time. It is simply the standard time of the next belt to the east.

For many years each community used its own local time, but as the use of railroads became more common, this was found inconvenient. In some communities the simple question, "What time is it?" might have several different answers. Local time would be in use; railroad time, probably the time of a nearby city, would also be in use; and sometimes a business owned by a non-resident would be run on a still different time. The leading countries of the World are now divided into time belts, the time in each belt differing from that of the adjacent belts by exactly one hour. (See Fig. 98.) For example, in the United States eastern time is five hours earlier than Greenwich time, central time six hours earlier, and so on.

In a few instances, particularly in islands, the time does not differ from the standard times by an exact number of hours. Hawaiian standard time is 10½ hours earlier than Greenwich time, and New Zealand standard time is 11½ later. In the vicinity of land, the boundaries between zones are modified so as to be in accord with the boundaries of the countries or regions using corresponding times. In the United States, the boundaries are usually the state boundaries.

The ship's clocks on vessels at sea are adjusted to the standard time of the successive zones as they are entered, but the instant at which the alteration is made is not necessarily that at which the vessel passes from one zone to another; the change of time is invariably one hour, the minutes and seconds remaining unaffected.

The preceding definitions are essentially those given in Bowditch, *The American Practical Navigator.* In the interest of accuracy, it is recommended that the distinction between the different kinds of time be sharply preserved, although that has not always been done.

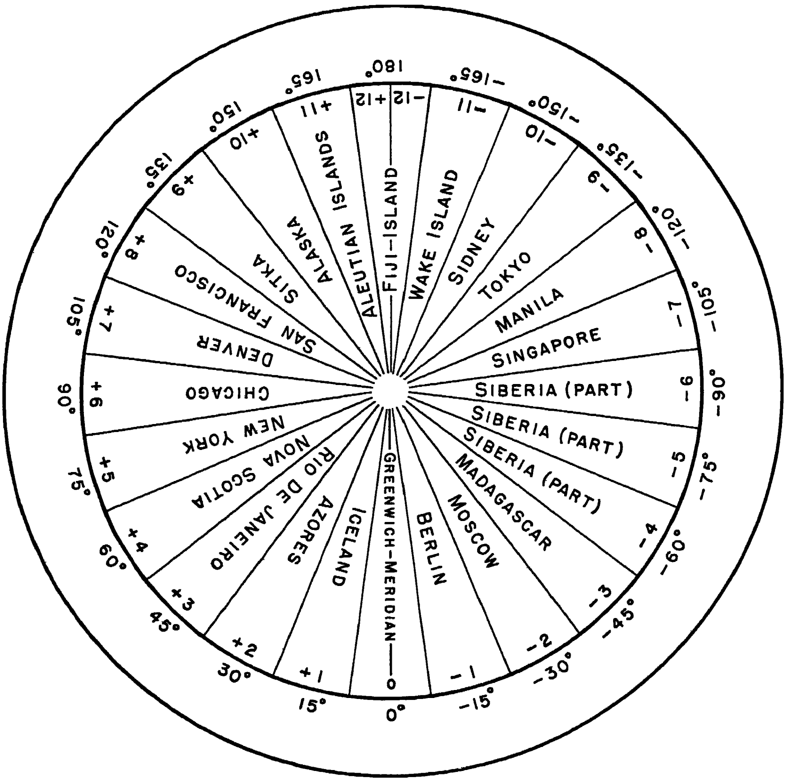


FIG. 98. Standard Time Zones of the World

For example, the British *Nautical Almanac* has dropped the distinction between astronomical time and civil time.

The International Date Line. From the preceding statements about time belts, it is obvious that if a person in the middle western United States could listen to reports of time by radio from the various belts on, for example, Wednesday at noon, he would find it 11:00 a.m. in the first belt west, 10:00 a.m. in the next, and earlier

hours Wednesday morning as belts from farther west are heard. From eastern belts the time would be 1:00 p.m., 2:00 p.m., toward late hours Wednesday night and early hours Thursday morning. Obviously, somewhere on the other side of the Earth, the time in adjoining belts must differ, not merely by an hour, but by a day. By international agreement, the change of date is made roughly along the 180° meridian from Greenwich, which lies almost entirely in the Pacific Ocean.

The following table, giving the time of noon, central standard time, Wednesday, will make the matter easier to understand.

TABLE IX. TIME IN DIFFERENT BELTS

	West			*East*	
Iowa City	12 noon	Wednesday	Iowa City	12 noon	Wednesday
Denver	11 a.m.	"	New York	1 p.m.	"
California	10 a.m.	"	Nova Scotia	2 p.m.	"
Alaska	9 a.m.	"	England	6 p.m.	"
Honolulu	7:30 a.m.	"	Germany	7 p.m.	"
180° merid.	6 a.m.	"	Rumania	8 p.m.	"
			India	11:30 p.m.	"
			Burma	12:30 a.m.	Thursday
			Philippines	2 a.m.	"
			Japan	3 a.m.	"
			Queensland	4 a.m.	"
			New Zealand	5:30 a.m.	"
			180° merid.	6 a.m.	"

The *date line* does not follow the meridian exactly. The Aleutian Islands use the American date, to agree with Alaska, although some of them are actually west of the meridian. Some of Siberia is east of the date line, but, of course, it all uses the same date. The groups of islands north of New Zealand all use the same date as New Zealand and Australia, although some are on the other side of the 180° meridian. A ship crossing the line changes the date at midnight near the line, rather than at the actual time of crossing.

An interesting fact is that an event may happen Thursday morning in Japan and be reported in the Wednesday afternoon papers in America. For example, the late emperor of Japan died in the early morning hours of Christmas Day, December 25, 1926. The afternoon papers of December 24 in the United States carried the report.

Distribution of Time. In most countries this is under government control. The leading nations maintain a regular program of observa-

tions on the Sun and stars at the government observatories. For the United States, time is furnished by the U. S. Naval Observatory in Washington, D.C.

Accurate time is obtained best from observations of the stars. A star appears in the telescope as a mere point, and can be observed more accurately than the Sun. As many stars as desired can be observed at the time of their meridian passage in a single night, while the Sun can be so observed only once in 24 hours. If necessary, the brighter stars can be observed by daylight, but conditions are better at night, which is another reason for preferring work on the stars. When the Sun is observed, shade glasses must be used to protect the observer's eye, and the heat may disturb the adjustment of the instrument. Observations on the Sun are discussed a year or more at a time and corrections to the tables derived. The time from day to day is based on observations of a selected list of stars.

Time is determined by photographing stars as they pass the zenith, using the *photographic zenith tube* shown on page 239. During exposure, the plate is driven by a 1000-cycle motor, and the time of passing the meridian is automatically recorded. By measuring the star images photographed, the right ascension of the center of the plate is accurately determined, and this should be the sidereal time of the crossing of the zenith. This instrument determines time with an uncertainty of only two or three thousandths of a second.

The three master clocks are *Shortt free pendulum* clocks, each controlled by an almost-free pendulum sealed in a bell jar and placed in a constant temperature vault in the basement below the clocks. These clocks are of such quality that the rates can be carried in thousandths of a second. The transmitting clock, which sends out the hourly signals over the telegraph and radio lines, is a *crystal clock*. This type of clock, instead of having a pendulum, is controlled by a crystal similar to that controlling the kilocycles of a radio station. The crystal is kept in vibration at its natural frequency which is of the order of 100,000 per second and is exceedingly uniform. By the use of harmonics, the rate is stepped down to exactly 1000 vibrations per second and is imposed on an electric current. This 1000-cycle current operates a synchronous motor which drives the clock just as a 60-cycle motor drives the ordinary household clock. Since each alternation lasts .001 second

and is controlled with great accuracy, time can be read from this clock in thousandths of a second. By turning a dial the clock can be advanced or retarded any desired number of thousandths.

This clock is kept running on Greenwich civil time. Regular comparisons are made with the Shortt master clocks in the vault. The master clocks run on Washington sidereal time, but the reduction to Greenwich civil time is simple, as will be explained later. On each of the twenty-four hours, signals are sent out over the radio, either long or short wave, or both, and once each day they are sent out over the telegraph lines. The radio signals are usually in error by less than a hundredth of a second, so that for ordinary purposes the error is negligible.

The signal consists of second beats, or ticks, and starts at five minutes of the hour, as shown in Table X.

Notice that in the time signal, beats are omitted (the twenty-ninth beat in each minute and also those from 55 to 59 inclusive) to mark the minute and the half-minute, so that there are several opportunities to check a timepiece. Further, the number of beats in the group sounded at the end of each minute indicates the number of minutes remaining before the hour signal: e.g., four beats in the first minute (beats 52 to 55 inclusive); three beats in the next minute (beats 53 to 55 inclusive), etc.

Timepieces. Newton's first law of motion states that a body subject to no forces moves with uniform motion. The ideal timepiece would, therefore, be a moving body subject to no forces. The closest approximation mankind has been able to produce is a delicate pendulum clock, mounted on a stone pier, sealed in a bell jar from which the air has been partially exhausted, electrically wound, with pendulum of invar (an alloy with small temperature change), and in a constant temperature vault. The best such clock is the Shortt free-pendulum clock. It has a seconds pendulum which swings almost independently in a bell jar and controls the clock proper, known as the slave clock only twice per minute. In this way the master pendulum is disturbed less by the clock mechanism than the pendulums in the best of the older clocks.

The *crystal* clock seems to be about as accurate as the Shortt, and may prove to be even more accurate when improved. It is a relatively new development.

Clocks, as a class, are not portable, and the *chronometer* was

TABLE X. U. S. NAVAL OBSERVATORY TIME SIGNAL

55^m	56^m	57^m	58^m	59^m
0^s	0^s	0^s	0^s	0^s
1	1	1	1	1
2	2	2	2	2
3	3	3	3	3
4	4	4	4	4
5	5	5	5	5
..	..			
25	25	25	25	25
26	26	26	26	26
27	27	27	27	27
28	28	28	28	28
—	—	—	—	—
30	30	30	30	30
31	31	31	31	31
32	32	32	32	32
33	33	33	33	33
34	34	34	34	34
35	35	35	35	35
..	..			
45	45	45	45	45
46	46	46	46	46
47	47	47	47	47
48	48	48	48	48
49	49	49	49	49
50	50	50	50	50
—	51	51	51	—
52	—	52	52	—
53	53	—	53	—
54	54	54	—	—
55	55	55	55	—
60	60	60	60	60[1]

invented to meet the need of an accurate portable timepiece. The chronometer has a large heavy balance, and what is known as a detached escapement. A chronometer usually beats half seconds. It is, therefore, easy to count seconds by listening to either a clock or chronometer while making some observation with the eye. The chronometer escapement is delicate, and consequently, chronometers are not satisfactory on small destroyers and submarines, and

[1] This is a sound 1 1/3 seconds long, its beginning marking the exact hour. The other signals last about 1/3 of a second.

would be of no value on airplanes. Even on large battleships and ocean liners, the navigator must not carry the chronometer about. He does not take it to the bridge when he makes his sextant observations, nor does he take it to the radio room for the time signals. A chronometer is hung in a special mount, called *gimbals*, so that it can remain level in spite of the rolling of the ship.

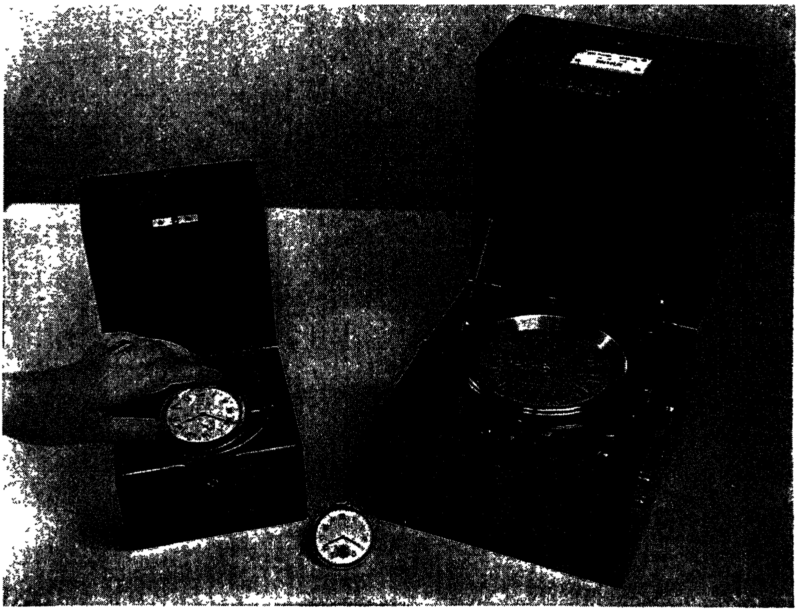


FIG. 99. Ship Watch, Pocket Watch, and Marine Chronometer. From Wylie's *Our Starland,* Lyons and Carnahan

In order to achieve portability one must go a step farther from the ideal of the moving body subject to no forces. For the heavy balance and detached escapement of the chronometer one must substitute the smaller balance and lever escapement of the *watch.* By making a watch larger than the standard railroad size some manufacturers have succeeded in producing excellent timepieces for the use of navigators. Some of these have been mounted in gimbals, chronometer fashion, for use on ships. These have been called ship watches.

A gimbal mounting cannot be used on an airplane, for a watch

so mounted would swing violently. The navigation watch for use on an airplane is called a *master watch.* This watch is held tightly

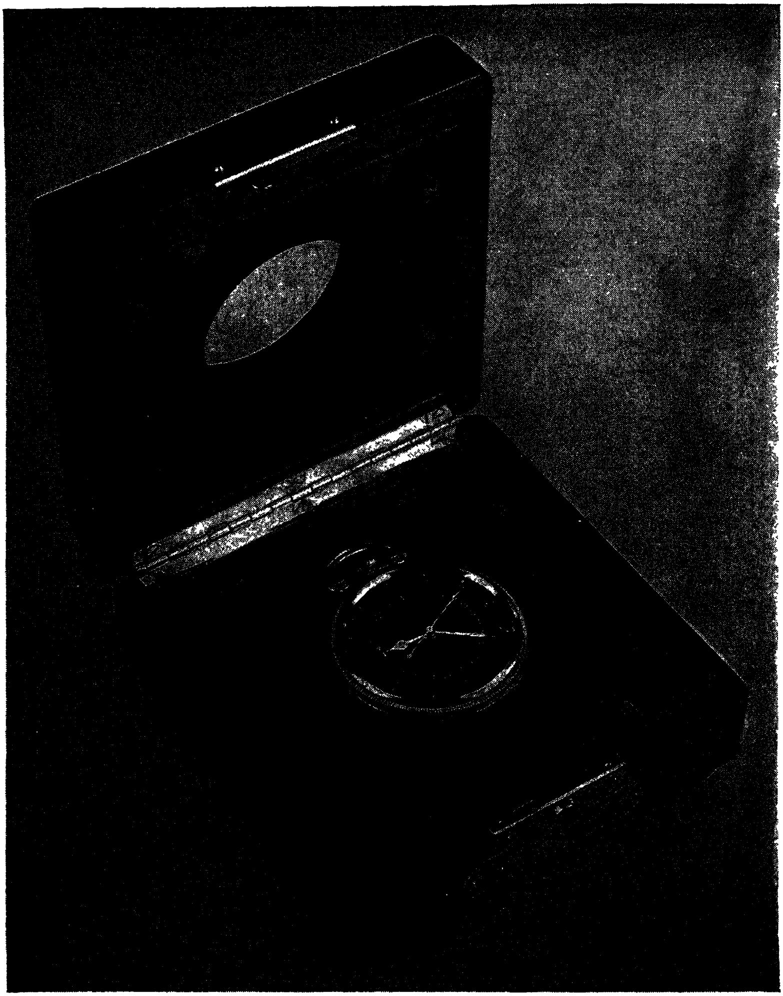


FIG. 100. Navigation Master Watch in Case, Cover Open. Photograph from Hamilton Watch Company

in a case and cushioned with sponge rubber. (See illustration.) It is kept in the case, except when removed for winding and set-

ting, and it should be fastened securely to the structure of the airplane in a convenient but safe position.

A watch is not so accurate as a chronometer or a clock, and even if it were, it would not be possible to time observations so accurately, since one cannot count seconds by the beat of a watch. The watch has, however, the great advantage of being less delicate, and its accuracy is quite sufficient for ordinary navigational work.

An accurate timepiece is ordinarily set to indicate approximately the true time, and then allowed to run as it will, the problem of the observer being to determine the amount of the *error* and its rate of change. The error is the quantity which must be subtracted algebraically from the chronometer reading to give the true time. With the chronometer slow the error is, therefore, negative, and with the chronometer fast, positive.

A chronometer is rarely set, but with the proper mechanism a watch can be set to the second without damaging the escapement, or affecting the rate appreciably. Modern aircraft master watches have a stop feature, which permits setting the second hand correctly, as for example by a time signal. When the second hand has been set, by stopping and then starting at the proper instant, the minute hand can be set to read the correct minute. To avoid errors of a minute, care should be taken to have the minute hand exactly on a minute division when the second hand is over "60."

The *hack watch* is the watch which the air navigator carries about while making his observations. The Weem's second-setting watch is a wrist watch with a rotating second dial. The second hand is not stopped, but the dial is rotated to indicate the correct second, and locked in that position. The minute hand is then set and, as previously stated, care must be taken to have it over a division when the second hand reads 60.

Care of Timepieces. Chronometers and watches should be wound carefully, and at the same hour each day. All timepieces should be protected from moisture, from electrical or magnetic disturbances, and from extremes of heat and cold. Master watches are furnished with plush-lined, rubber-cushioned cases in which they should be kept. Chronometers should not be carried about for observations with sextants, or comparison with radio signals. Good watches can be used for such work. If it is necessary to move a chronometer, especially avoid a rotary motion, as with the heavy balance such

motion will damage the delicate escapement. It is good practice, when moving a chronometer, to notice the direction of the figure 12 on the dial, and keep it in that direction while carrying the chronometer.

Occasionally a watch gets wet. When this happens the best procedure is to immerse it promptly in gasoline. If at sea, or where a jeweler cannot be reached immediately, take it from the gasoline and immerse it in oil until it can be given the proper attention.

FIG. 101. Second-Setting Watch. Photograph from Weems System of Navigation

Comparison of Timepieces. Before starting the actual comparison of timepieces or timing of observations, it is well to practice reading a watch to the second. In the determination of longitude and latitude on shore it is worthwhile to time sextant observations to the fraction of a second. On a ship or plane they must be timed to the second. The average student who has had no practice in reading to the second makes mistakes, not so much in estimating fractions of a second, which are unimportant, as in reading the minutes, which are important.

If the hour hand is at approximately 10, and the minute hand at 11, the average student will read the time correctly as $9^h\ 55^m$, not $10^h\ 55^m$. But if the minute hand is near 20, and the second hand at 55, the same student often records the time as $20^m\ 55^s$, instead of

$19^m\ 55^s$. Mistakes of two or more minutes occur with surprising frequency at first, but after only a little practice, are almost never made.

For practice, a good plan is to lay five or six watches, set to read odd hours and minutes, at about two-foot intervals around the edge of a table. The instructor should have ten or a dozen students form a line, and he should then tap the table at twenty-second intervals. On the first tap, one student records the reading of the first watch. On the second tap, the first student reads the next watch, and a second student reads the first watch. The instructor should continue tapping until all students have read all the watches twice. If the instructor records the time indicated by the master watch both times the first student reads the first watch, the difference of the two readings should be the same as the difference between each pair of readings by each student. This practice should be continued until the differences agree within a second.

The student should next practice the *counting of seconds* by a clock or chronometer. Looking at the face of the clock or chronometer, the student starts the count of the seconds to agree with the face reading, then looks away and continues the count. The students should work in pairs, so that while one counts by the beat, the other can watch the face of the clock or chronometer to be sure that the count is continued correctly. In counting, the start of the new minute should be called zero, not 60. This is in agreement with both scientific and popular custom. For example, a train is scheduled to leave at 12:00, not 11:60.

A stop watch can be used to check the accuracy of a student's count. Let him hold the watch in his hand face down while he listens to the beat of the clock or chronometer. When he has the cadence of the beat, he should start the watch and begin to count the seconds without looking at the clock or watch. On the count of 20, he should stop the watch and compare his count with the elapsed time. The student should start his count, as he starts the watch, on "mark," not on "one," or his time will be erroneous.

In checking timepieces by a *time signal*, the carrying of the count is not absolutely necessary, but it adds to the accuracy of the comparison. A count of the seconds should be carried by the beat of the signal, the reading of the watch or other timepiece being re-

corded at zero seconds and at 30 seconds of the signal. The omitted beats mark these points in the signal. (See Table X.)

A good problem for practice is the *comparison* of *two watches*, watch *A* and watch *B*, with a chronometer, *C*, and with one an-

FIG. 102. A Marine Chronometer. Photograph from Hamilton Watch Company

other. The student should compare the chronometer with each watch by carrying the second count of the chronometer while looking at the watch. On the count of "zero," or "30," record the seconds shown by the watch, then fill in the hours and minutes for chronometer and watch while looking from one to the other. Re-

member to record the seconds before noting the minutes. To compare the watches, look at watch *A* and count the seconds until the cadence of the count is obtained. Then just before zero seconds or 30 seconds look at watch *B* while continuing the count on *A*; note

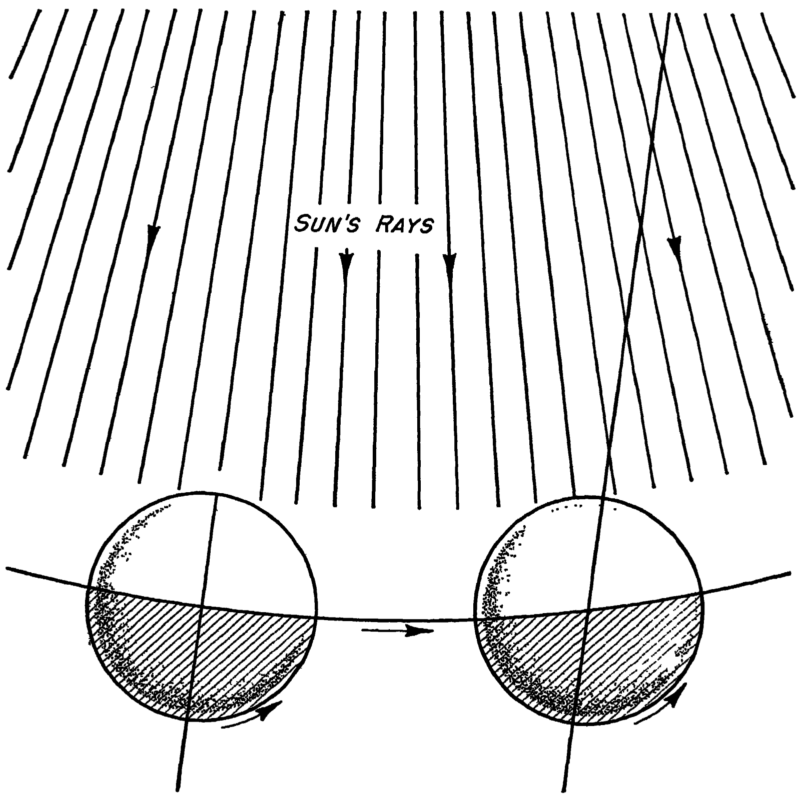


FIG. 103. Relation between Sidereal Day and Mean Solar Day

the reading of the seconds on *B* at the count of "zero," or "30," and record it. Then, as before, note and record the minutes on each watch.

From the comparisons made in this way we form the following differences, C − B, C − A, and A − B. If we now subtract C − A from C − B, we obtain another value for A − B. The first value of A − B depends on the intercomparison of the watches. The second

value depends on the comparison of each watch with the chronometer. The two values should agree within a second.[2]

Reduction of Sidereal Time to Mean Solar Time. The approximate relation between *sidereal* time and *mean solar time* is simple. Fig. 103 illustrates the fact that the solar day is longer than the sidereal day. Since the Earth revolves once about the Sun in a year, the Sun loses a rotation about the Earth as compared to the vernal equinox in that time, causing sidereal time to gain a day in a year. Since there are 24 hours in a day and 12 months in a year, the gain is approximately 2 hours per month. Since the Sun is at the vernal equinox on about March 21 of each year, sidereal noon and local apparent noon therefore occur together on about that date. But as a result of the equation of time, the Sun is then about seven minutes slow, so that sidereal noon and mean noon are together on about March 23. This gives us the following simple rule for obtaining sidereal from mean solar (astronomical) time, and vice versa.

$$\text{Sidereal} = \text{Mean Solar} + 2\ (\text{months after March } 23)$$
$$\text{Mean Solar} = \text{Sidereal} - 2\ (\text{months after March } 23).$$

The sidereal time is the right ascension of stars on the meridian, so this rule is convenient for figuring mentally what stars will be in good position for observation at a certain hour in the evening. As an example, find the sidereal time, or the right ascension of stars on the meridian, at 9:00 p.m., July 4. If we say that July 4 is $3\frac{1}{4}$ months after March 23, we have from the above rule

$$\text{Sidereal} = 9 + 2\ (3\tfrac{1}{4}) = 15\tfrac{1}{2}.$$

The sidereal time is, therefore, about $15\frac{1}{2}$, or $15^h\ 30^m$. By looking for that right ascension on a star chart, one can see what stars are near the meridian at that hour on the evening of July 4.

The preceding method suffices for very rough work only, but there are many times when an accurate value of the Greenwich or local sidereal time is desired. For this work, the *Nautical Almanac* tabulates two quantities, first, the "Sidereal Time of 0^h Civil Time at Greenwich," or the sidereal time of Greenwich mean midnight,

[2] In subtracting times, note that if seconds must be "borrowed" from the minutes column, or minutes from the hour column, the number borrowed is 60, not 100.

and second (in Table VI, of the *Nautical Almanac*) the gain of sidereal time in a given mean solar interval.

Greenwich Sidereal Time. Since civil time is the interval after midnight, it is evident that the Greenwich sidereal time for a certain Greenwich civil time is obtained by adding together the sidereal time at midnight taken from the *Nautical Almanac*, the civil time or interval after midnight, and the Table VI correction,

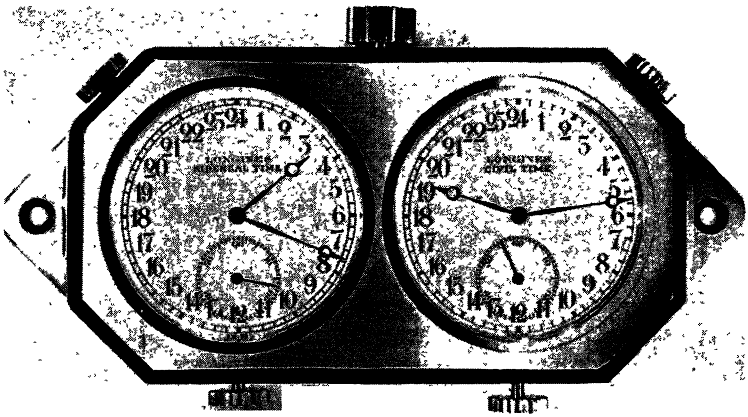


FIG. 104. Navigation Watch Showing Civil Time and Sidereal Time. Photograph from Weems System of Navigation

or gain of sidereal, since midnight. Time signals are heard on exact hours. Suppose that the Greenwich sidereal time of the signal at Greenwich civil time 17^h 00^m December 25, 1943, is desired. The reduction is

Greenwich sidereal time midnight	6^h	10^m	$32^s.0$	Nautical Almanac
Greenwich civil time	17	00	0.0	
Table VI in Nautical Almanac (17:00:00)			47.6	
Greenwich sidereal time	23	13	19.6	

It is obvious that the last two quantities used do not depend upon the date. The civil time and Table VI can be combined into a "reduction" to be added to the Greenwich sidereal time of midnight whenever a time signal is received at that hour. The following table gives these reductions for the various hours of Greenwich time.

TABLE XI. REDUCTION TO GREENWICH SIDEREAL TIME

Greenwich Civil Time	*Reduction*		
1	1^h	0^m	$9^s.9$
2	2	0	19.7
3	3	0	29.6
4	4	0	39.4
5	5	0	49.3
6	6	0	59.1
7	7	1	9.0
8	8	1	18.9
9	9	1	28.7
10	10	1	38.6
11	11	1	48.4
12	12	1	58.3
13	13	2	8.1
14	14	2	18.0
15	15	2	27.8
16	16	2	37.7
17	17	2	47.6
18	18	2	57.4
19	19	3	7.3
20	20	3	17.1
21	21	3	27.0
22	22	3	36.8
23	23	3	46.7

With this table, checking a master watch running on Greenwich sidereal time is a simple matter if it is known to be within a few seconds of the correct time. Record the reading of the watch on the beat of the signal, marking the hour. Then take from the preceding table the reduction given in the seconds column only for that hour. Take from the *Nautical Almanac* the "Sidereal Time of 0^h," again using the seconds column only. Add to this the reduction, and the resulting sum should be the seconds reading of the watch on the signal.

Local Sidereal Time. You have read that difference in time is equal to difference in longitude, and that Greenwich time − Local time = Longitude West. From this it follows that the reduction to local sidereal time can be obtained by subtracting the longitude from the reduction to Greenwich sidereal time as given in Table XI. If the master watch is known to be within a few seconds of correct

time, seconds only need be carried in the reduction. The following problem shows the work.

Example: The time signal at 17^h Greenwich Civil Time (G. C. T.) is received at Urbana, Illinois, on January 5, 1943. A master watch running on local sidereal time reads $48^s.5$. The longitude of Urbana is $5^h\ 52^m\ 53^s.9$. Find the error of the watch.

Reduction to Greenwich	= $47^s.6$	Table XI
Longitude (Subt.)	= 53.9	
Reduction to Urbana	= 53.7	
Sidereal time for Greenwich 0^h Jan. 5	= 51.7	Nautical Almanac
Urbana sidereal	= 45.4	
Watch reading	= 48.5	
Watch error	= +3.1	

At a university or a training camp where a timepiece is kept running on local sidereal time, a table for reduction to local sidereal should be formed by subtracting the longitude from each of the quantities in Table XI, and adding 24 hours to the tabular quantity if necessary. It may be more convenient to use as arguments for this table, the hours of standard time of that belt, instead of hours of Greenwich time. The tabular quantities, of course, will not be changed by this change in the arguments. The local sidereal time of a signal is the same whether it be considered as 17^h Greenwich Civil Time (G. C. T.) or as 11^h Central Standard Time (C. S. T.).

If such a table of local reductions has been prepared, the work is quite brief where seconds only need be carried. The preceding example reduces to the following:

Reduction to Urbana	$53^s.7$	
Greenwich sidereal time, 0^h, Jan. 5	51.7	Nautical Almanac
Urbana sidereal time (105.4 − 60)	45.4	
Watch reading	48.5	
Watch error	+3.1	

Where regular comparisons of a sidereal watch with a time signal are made, seconds only need be used for the great majority of comparisons. It is desirable to check the minutes occasionally, however. For an example, the Greenwich sidereal time for the signal at Greenwich civil time, $17^h\ 00^m$, December 25, 1943, using Table XI and carrying minutes, is obtained as follows:

Reduction (from Table XI)	2^m	$47^s.6$	
Greenwich sidereal time, 0^h	10	32.0	Nautical Almanac
Greenwich sidereal time	13	19.6	

If seconds only are carried, the reduction to Greenwich sidereal time by using Table XI would give the same result as the above, but without the minutes column.

Mean Solar Time to Local Sidereal Time (General). A considerable number of the reductions from mean solar to sidereal time, and vice versa, can be made for exact hours of Greenwich or standard time, and for these the preceding simplified methods can be used, carrying minutes, or even hours, in the reduction when necessary. Often, however, it is necessary to calculate the Greenwich sidereal or the local sidereal time for a mean solar time involving minutes, seconds, and a fraction of a second. A general method of reduction is needed therefore. In the general reduction from *standard time to local sidereal time*, reduce standard time to Greenwich civil time by adding the longitude (west) of the standard meridian. Then reduce the Greenwich civil to Greenwich sidereal by the use of the *Nautical Almanac* quantities. Then reduce the Greenwich sidereal to local sidereal by subtracting the longitude of the local station. The following problem illustrates this method.

Find the Iowa City, Iowa, sidereal time of $8^h\ 35^m\ 57^s.5$ p.m. (central standard time), on the evening of February 10, 1943. The longitude of Iowa City is $6^h\ 6^m\ 8^s.0$ west.

1. Central standard time	= 8^h	35^m	$57^s.5$ p.m.	
2. Central standard time (civil) (item 1 plus 12^h)	= 20	35	57.5	
3. Longitude 90° meridian (add)	= 6	0	0.0	
4. Greenwich civil time (Feb. 11) (items 2 plus 3 minus 24^h)	= 2	35	57.5	
5. Table VI (add) (the gain in the sidereal time interval for the 2h 35^m 57.5^s solar time interval)	=	0	25.6	Nautical Almanac
6. Greenwich sidereal interval after midnight (items 4 plus 5)	= 2	36	23.1	
7. Sidereal time for Greenwich 0^h (Feb. 11)	= 9	20	44.3	Nautical Almanac
8. Greenwich sidereal time (items 6 plus 7)	= 11	57	7.4	
9. Longitude, Iowa City (Subtract)	= 6	6	8.0	
10. Iowa City sidereal time (items 8 minus 9)	= 5	50	59.4	

The reduction from *local sidereal* to *Greenwich*, or *standard mean solar*, time is of relatively frequent occurrence. For example, a star

may be observed on the meridian, and timed by a chronometer or watch running on standard time. The general plan is to reduce the local sidereal to Greenwich sidereal by adding the local longitude (west). Then reduce the Greenwich sidereal to Greenwich civil

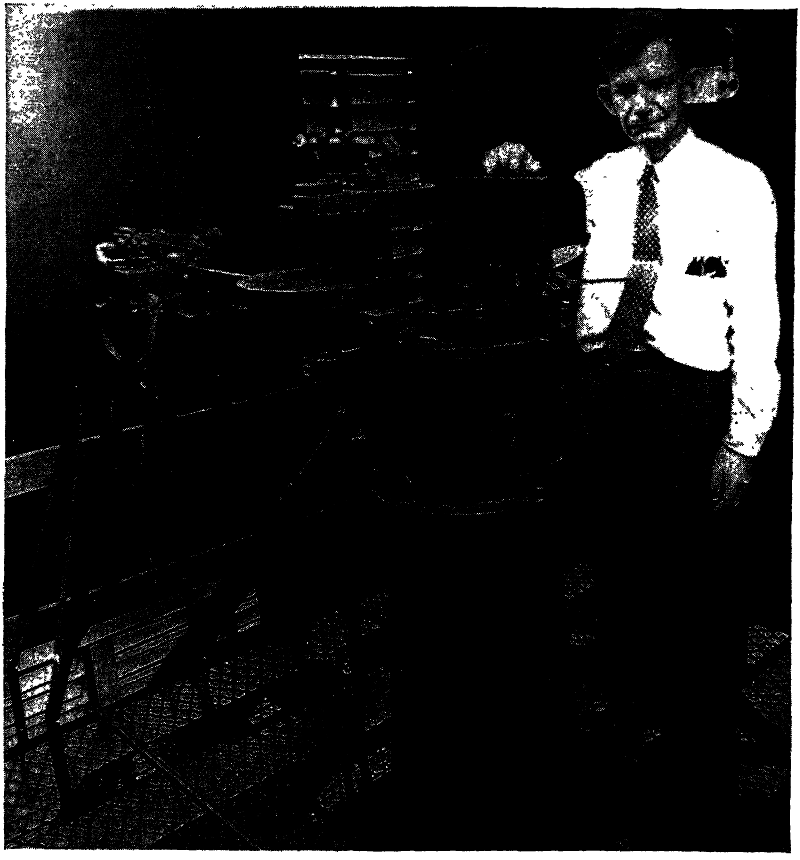


FIG. 105. Photographic Zenith Tube for Determining Time and Latitude. Photograph from U. S. Naval Observatory

time by the *Nautical Almanac* quantities. Then reduce the Greenwich civil to standard time by subtracting the longitude of the standard meridian. The following problem illustrates the method.

Example: The star Betelgeuse, right ascension 5^h 52^m $5^s.7$ is observed on the meridian on the evening of February 10, 1943, at

$8^h\ 15^m\ 34^s.5$ p.m. by a watch running on eastern standard time. The star was observed at Boston, Massachusetts, whose longitude is $4^h\ 44^m\ 19^s.1$ west. Find the watch error.

The right ascension of a star on the meridian is the local sidereal time. Hence this problem requires a reduction from local sidereal to eastern standard time. Since 8:15 p.m. eastern time is 1:15 a.m. the next day at Greenwich, the sidereal time of Greenwich midnight must be taken out for February 11.

1. Local sidereal time (Right ascension of Betelgeuse)	=	5^h	52^m	$5^s.7$
2. Longitude Boston (add)	=	4	44	19.1
3. Greenwich sidereal time (items 1 plus 2)	=	10	36	24.8
4. Sidereal time for Greenwich 0^h (Feb. 11, from Nautical Almanac) (Subtract)	=	9	20	44.3
5. Greenwich sidereal interval after midnight (items 3 minus 4)	=	1	15	40.5
6. Table V (from Nautical Almanac, subtract) (This item gives the loss in solar time during the sidereal interval given in item 5)	=		0	12.4
7. Greenwich civil time (Feb. 11) (items 5 minus 6)	=	1	15	28.1
8. Longitude 75° meridian (Subtract)	=	5	0	0.0
9. Eastern standard time (Feb. 10) (items 7 plus 24^h minus item 8)	=	20	15	28.1
10. Watch reading	=	20	15	34.5
11. Watch error	=			+6.4

Determination of Time. In practice, the determination of time is the determination of the error of a timepiece. The reading of a timepiece, at the instant of some observation, is noted. From the observation, the corresponding time is calculated, and compared with the reading of the timepiece. An astronomer, however, can obtain the time roughly by merely looking at the stars and making a simple mental calculation. Rules have been developed so that anyone can obtain the time in such a way from certain of the more important stars, or groups of stars. Below is given a method of obtaining the approximate time from the Big Dipper, and following this, some methods of accurate time determination.

Everyone, who has watched the Big Dipper, has noticed that it appears to circle counterclockwise about the pole star. Since this apparent motion is due to the rotation of the Earth, and since the Earth turns on its axis once in 24 hours, the Dipper circles about the pole star once in 24 hours. If the northern sky is thought of as a giant clock face, with the hour hand pivoted at the pole star and extending to the pointer stars of the Big Dipper, the reading of this giant clock will decrease one hour for each two hours of elapsed

time. For example, if the pointers are out to the left (nine o'clock reading) at 7:00 p.m., they will be directly below (six o'clock reading), six hours later, at 1:00 a.m.

Looking at the Dipper occasionally throughout the year, one notices that its position as seen in the early evening sky changes. This is due to the revolution of the Earth about the Sun. As the Earth spends twelve months in its circuit, and there are 12 hours on the clock face, the reading of the giant clock in the northern sky will change one hour per month, for a person watching at the same time each evening.

From these considerations, the following rules for obtaining *time from the Big Dipper* have been formulated:

Imagine the northern sky to be a giant clock face, the hour hand extending from the North Star to the pointers of the Big Dipper.

1. Read the time by this clock, estimating the quarter hour.
2. Add to this reading the number of months since New Year's Day, to the nearest quarter month. This reduces the sky reading to what it was at this particular hour at night on January 1. Remember that the motion of the Earth about the Sun changed the reading one hour per month.
3. Double the above sum (there are 24 hours in the day and but 12 on the sky clock face).
4. Subtract from $16\frac{1}{4}$, or, if the doubled sum is larger than $16\frac{1}{4}$, from $24 + 16\frac{1}{4} = 40\frac{1}{4}$. This constant, $16\frac{1}{4}$, is double the reading of the northern sky at noon on New Year's day. We saw that the sky clock reading decreased one hour for each two hours of elapsed mean time. Therefore, if the sky reading at some other hour on January 1 is doubled, as by Rule 3, and subtracted from the above constant, the result will be the hours of mean time after noon, or the local mean time p.m. If it is over 12, subtract 12 and call it a.m.; that is, 13:00 p.m. is 1:00 a.m., 14:00 p.m. is 2:00 a.m., and so forth.

Example: On the evening of February 22 the reading of the northern sky is estimated to be 2:30. Required: the local mean time.

The time $2{:}30 = 2\frac{1}{2}$. It is $1\frac{3}{4}$ months since New Year's day; $2\frac{1}{2} + 1\frac{3}{4} = 4\frac{1}{4}$; doubling, $4\frac{1}{4} \times 2 = 8\frac{1}{2}$; subtracting, $16\frac{1}{4} - 8\frac{1}{2} = 7\frac{3}{4}$; it is $7\frac{3}{4}$ hours since noon, or 7:45 p.m.

The following are some of the more important methods of determining the time accurately.

1. As the stars pass the zenith, they are *photographed on a moving plate*. The plate follows the stars automatically, and the time of its passing the zenith is recorded automatically. This gives sidereal time, since the right ascension of stars on the meridian is equal to the sidereal time. This method, used at the U. S. Naval Observatory, was referred to on page 224, and a photograph of the instrument is shown in Fig. 105.
2. With a *transit instrument* pointing on the *meridian*, note the time a star passes the meridian. Repeat for several stars. The most accurate method is following the star with a double thread, and letting the times be recorded automatically, perhaps ten threads before and ten threads after crossing the meridian. Another method is pressing the key as the star seems to pass behind each of, let us say, ten threads. The key breaks an electric circuit and in this way records the time. A third way of noting the time is by carrying mentally the second beat of a chronometer or clock and estimating the tenth of second at which the star seems to pass behind each thread. This is the least accurate of the transit methods.

   Transit observations of a star give sidereal time, since the sidereal time each star passes the meridian is its right ascension.

   The Sun is observed occasionally with the smaller transit instruments for time. The Sun passes the meridian at local apparent noon, and by applying the equation of time, local mean time is obtained.
3. The transit methods cannot be used when observing with a sextant, since the sextant measures altitudes rather than meridian passage. On land, however, *equal altitudes*, one in the east and one in the west, can be used as the equivalent of a meridian passage. It is obvious that, since the Earth rotates uniformly, the mean of the times for a star in the east at a certain altitude, and in the west at the same altitude, must be the time of meridian transit. For the Sun, there usually must be a small correction because of motion north or south. Tables have been prepared from which this correction can be taken, and time is determined regularly from equal altitudes of the Sun.

In the case of a star, the long wait at night while the star moves from the eastern to the western sky is inconvenient. It is simpler, therefore, to observe *two stars* at the *same altitude*, one star in the eastern sky and the other in the western sky at the same altitude. The time can then be calculated readily from a simple formula which involves the difference in declination of the two stars, but not the altitude. The navigator usually cannot use this method because his ship or plane will have moved to a different location by the time the second altitude is observed.

4. One can observe a *single altitude*, or set of altitudes, of a heavenly body, and calculate the hour angle if the latitude and declination are known. For the Sun, the hour angle is equal to the local apparent time (astronomical), as you have read. For a star, the right ascension plus the hour angle is equal to the sidereal time. This is the method the navigator must use in general. Formulas and tables for obtaining the hour angle will be discussed in the next chapter.

Exercises

1. What is an hour circle and what is an hour angle? When is it considered plus and when negative?
2. What is meant by the transit of a celestial object? What is the upper and what is the lower transit?
3. What three times are employed in astronomy and how is each defined?
4. What is the equation of time? How is it determined?
5. What is the astronomical time on August 16, at 3 a.m., 4 p.m., and 11 p.m. respectively? What is the civil time at 1:00, 7:23, and 18:52 astronomical time?
6. What is the sidereal time when Vega, Canopus, and Sirius respectively, are on your meridian? (Use map in back of either the *American Nautical* or *Air Almanac* for star positions.)
7. If the hour angle of Fomalhaut is $+ 23° 14' 25''$, what is the sidereal time?
8. If the local time is 2:15:43 p.m. and the time by a clock running on Greenwich time is 4:45:16 p.m., what is the longitude?
9. What is standard time? How many time belts are there, and how

wide are they? Are all standard times on the hour and does the entire world use standard time?

10. What is the local mean time at longitude 6:36:49 if the central standard time is 3:13.57 p.m.?
11. What is the international date line? Where is it?
12. What are the most accurate timepieces man has produced?
13. What is a hack watch and for what is it used?
14. If it is 6:00 a.m. at Greenwich on June 30, 1943, what is the sidereal time? Find the sidereal time for 2:00 p.m., September 10, 1943, at Greenwich. Use the approximate method, and then the exact method, with the *Nautical Almanac.*
15. What is the sidereal time at longitude 123° 45′ W at 7:24:43 p.m. Pacific time on the evening of July 4, 1943?
16. Calculate the Pacific standard time when Vega crosses the meridian at Mount Wilson, California, longitude 7:52:14.3 W, on May 1, 1943.
17. If the Big Dipper sky clock reads 6:30 on the evening of October 2, 1943, what is the local mean time?
18. Give some methods for accurate determination of time. (a) At an astronomical observatory. (b) When using a sextant on land. (c) When using a sextant on a ship or plane.

☆ XII ☆

Celestial Navigation

Celestial navigation is the art of determining one's position on the Earth from observations of celestial bodies such as the Sun, Moon, stars, and planets.

For flights of 500 to 1,000 miles in ordinary civil life, celestial navigation is seldom used. For such distances, the combined use of piloting, dead reckoning, and the radio ordinarily affords satisfactory results. With the development of large nonstop transports, capable of flying great distances, longer and longer flights have been included in air transportation schedules. Regular flights across both the Atlantic and Pacific are now regularly scheduled. For flights such as these celestial navigation is not only practical, but necessary. In time of war, long flights must be made over enemy territory at night, without the guidance of radio beams and beacon lights.

Efficient operation demands that long flights be made at high altitudes, and a large percentage of such flights are above any overcast. This prevents the direct determination of drift and ground speed, and makes dead reckoning of doubtful value; it does not affect radio, except in the event of complete failure or excessive static, as in a magnetic storm, and it does not affect celestial navigation. For longer flights, then, especially over ocean routes, or enemy territory, celestial navigation becomes the primary method.

The accuracy of the results depends on the skill of the observer, the instrumental equipment, and the conditions under which the sextant observations are taken. By means of astronomical observations a surveyor on the solid Earth can determine the geographic location of his position within a few yards; on a ship at sea, position can usually be determined within a mile or two. Under aver-

age conditions in the air, an accuracy of 5 to 10 miles should be obtained, although considerably greater errors may occur with a light airplane and bumpy air. Since a single observation may be greatly in error, it is common practice to take from 5 to 10 observations in quick succession, and to determine the position from the average of the observations. Obviously, the better the flying conditions the smaller the number of observations needed for a satisfactory determination.

Corrections to Observed Altitudes. The *true altitude* of a heavenly body at any place on the Earth's surface is the altitude of its center, as it would be measured by an observer at the center of the Earth, above the plane passed through the center of the Earth at right angles to the direction of the zenith.

The *observed altitude* of a heavenly body may be converted to the true altitude by the application of the following corrections: *index correction, dip, refraction, parallax,* and *semidiameter.* The corrections for parallax and semidiameter are of inappreciable magnitude in observations of the fixed stars, and with planets are so small that they need only be regarded in refined calculations. In observations with the artificial horizon of mercury, or with the bubble sextant, there is no correction for dip.

The *index error* of a sextant is the error of its indications resulting from the fact that when the index and horizon mirrors are parallel, see Fig. 108, page 251, the zero of the vernier does not coincide with the zero of the scale. Having made the adjustments of the index and horizon mirrors and of the telescope, it is necessary to find that point of the arc on which the zero of the vernier falls when the two mirrors are parallel, for all angles measured by the sextant are reckoned from that point. If this point is to the left of the zero of the limb, all readings will be too great; if to the right of the zero, all readings will be too small.

If it is desirable that the reading should be zero when the mirrors are parallel, place the zero of the vernier on zero of the arc; then, by means of the adjusting screws of the horizon glass, move that glass until the direct and reflected images of the same object coincide. This adjustment is not essential, since the correction may readily be determined and applied to the reading, but in navigation it will be convenient to be relieved of the necessity of correcting each angle observed. The sextant should never be relied upon

for maintaining a constant index correction, and it should be checked frequently.

Dip of the horizon is the angle of depression of the visible sea horizon below the true horizon, which is due to the elevation of the observer's eye above the level of the sea. In Fig. 106 suppose *A* to be the position of an observer whose height above the level of the sea is *AB*. *CAZ* is the true vertical at the position of the ob-

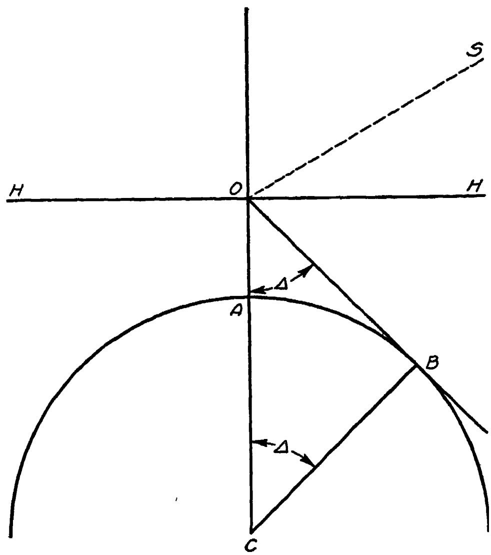


FIG. 106. Schematic View of the Dip of the Horizon

server, and *AH* is the direction of the true horizon, *S* being an observed heavenly body. Draw *ATH′* tangent to the Earth's surface at *T*. Disregarding refraction, *T* will be the most distant point visible from *A*. Owing to refraction, however, the most distant visible point of the Earth's surface is more remote from the observer than the point *T*. The dip of the horizon is the angle between the true horizon and the apparent direction of the sea horizon. Values of the dip are given in a table on the back of the *Air Almanac* for various heights of the observer's eye, and in the calculation of the table, allowance has been made for the effect of atmospheric refraction as it exists under normal conditions.

Atmospheric *refraction* can be represented by the following formula with sufficient accuracy for any work with the sextant. In this formula, b is the barometer reading in inches, t is the temperature in degrees Fahrenheit, and h is the observed altitude.

$$R'' = \frac{983b}{460 + t} \cot h.$$

The denominator represents the temperature on the absolute scale, and the coefficient 983, is empirical. It will be observed that an increase in the barometer reading, which means an increase in the density of the air, increases the refraction; while a rising temperature, which decreases the density, has the opposite effect. A rough estimate to the hundredth of an inch for the barometer reading and a record of the temperature to the nearest degree Fahrenheit is quite sufficient. The formula represents the refraction within

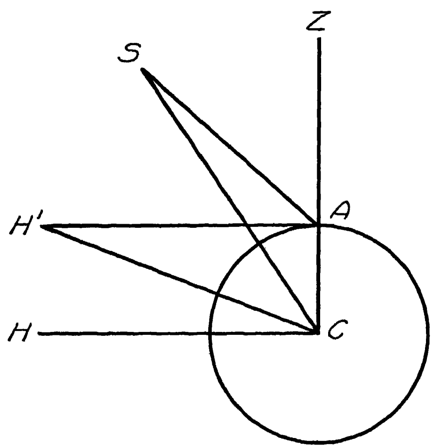


FIG. 107. Parallax of a Heavenly Body as Used in Navigation

a small fraction of a second of arc for altitudes over 25°. For an average temperature and barometer, the error is about 0.″5 at 20°, 1″ at 18°, 5″ at 12°, and 10″ at 10° altitude. For smaller altitudes the error increases rapidly.

For ordinary purposes of air navigation, however, the table in the back of the *Air Almanac*, which has been computed for average conditions, is sufficient. The correction for refraction should be subtracted from the observed altitude.

The *parallax* of a heavenly body is, in general terms, the angle between two straight lines drawn to the body from different points. In celestial navigation, this is the difference between the positions of a heavenly body as seen at the same instant from the center of the Earth and from a point on its surface.

The zenith distance of a body, S (Fig. 107), seen from A, on the surface of the Earth, is ZAS; seen from C it is ZCS. The parallax is the difference of these angles, $ZAS - ZCS = ASC$. Parallax in altitude is, then, the angle at the heavenly body subtended by the radius of the Earth.

If the heavenly body is on the horizon, as at H', the radius, being at right angles to AH', subtends the greatest possible angle at the body for the same distance. This angle is called the *horizontal parallax* and is denoted by H. P. The parallax is smaller as the bodies are farther from the Earth, as will be evident from the figure. Let

par. = parallax in altitude, ASC;
$Z = SAZ$, the apparent zenith distance (corrected for refraction);
$R = AC$, the radius of the Earth;
$D = CS$, the distance of the object from the center of the Earth.

Then, since $SAC = 180° - SAZ$, the triangle ASC gives:

$$\sin par. = \frac{R \sin Z}{D}.$$

If the object is on the horizon at H', the angle $AH'C$ is the horizontal parallax, therefore the right triangle $AH'C$ gives:

$$\sin \text{H. P.} = R/D.$$

Substituting this value of R/D in the above,

$$\sin par. = \sin \text{H. P.} \sin Z.$$

If $h = SAH'$, the apparent altitude of the heavenly body, then $Z = 90° - h$; hence,

$$\sin par. = \sin \text{H. P.} \cos h.$$

Since the parallax, *par.*, and H. P. are always small, the sines are nearly proportional to the angles; therefore,

$$par. = \text{H. P.} \cos h.$$

The Moon is the only heavenly body close enough for the parallax to be appreciable in celestial navigation. The *Air Almanac* gives for each day the parallax of the Moon for altitudes up to 80°. If greater accuracy is desired, the horizontal parallax of the Moon, or of the brighter planets, can be interpolated from the *Nautical Almanac*, and the parallax at the observed altitude calculated. The parallax correction is always added to the observed altitude, and it must be applied to observations on the Moon whether the sea horizon, a mercury horizon, or a bubble sextant is used.

The *semidiameter* of a heavenly body is half the angle subtended by the diameter of the visible disk at the eye of the observer. For the same body the semidiameter varies with the distance; thus, the difference of the Sun's semidiameter at different times of the year is due to the change of the Earth's distance from the Sun; and similarly, the Moon's semidiameter varies throughout the month. As observed in navigational instruments, the planets show no sensible disk, and hence, no semidiameter correction is necessary for them. Nor is any correction needed for the stars, as even the largest telescopes now in use do not show the stars as sensible disks.

The semidiameter is to be added to the observed altitude in case the lower limb of the body is brought into contact with the horizon, and to be subtracted in the case of the upper limb. When the artificial horizon is used, the limb of the *reflected* image is that which determines the sign of this correction. This correction is added to the lower and subtracted from the upper.

The Navigator's Equipment. In addition to the marine chronometer, or the aircraft master watch, mentioned in the chapter on time, the navigator needs the sextant for observing the altitude of the heavenly bodies, and an almanac which tabulates their positions from day to day. Other aids, such as slide rules, tables to facilitate the reduction of observations, and star altitude curves will be referred to in connection with the determination of the observer's position.

The *sextant*, by reason of its small dimensions, its accuracy, and the fact that it does not require a permanent or a stable mounting but is available for use under the conditions existing on shipboard, or on an airplane, is a most important instrument for the purposes of the navigator. It is an instrument for measuring the angle between two objects by bringing images into coincidence at the eye

of the observer. The rays of light are received directly from the one object and by reflection from the other. The angular distance is obtained by measuring the inclination of the reflecting surfaces. While the sextant is not capable of the same degree of accuracy as fixed instruments, its measurements are sufficiently exact for navigation.

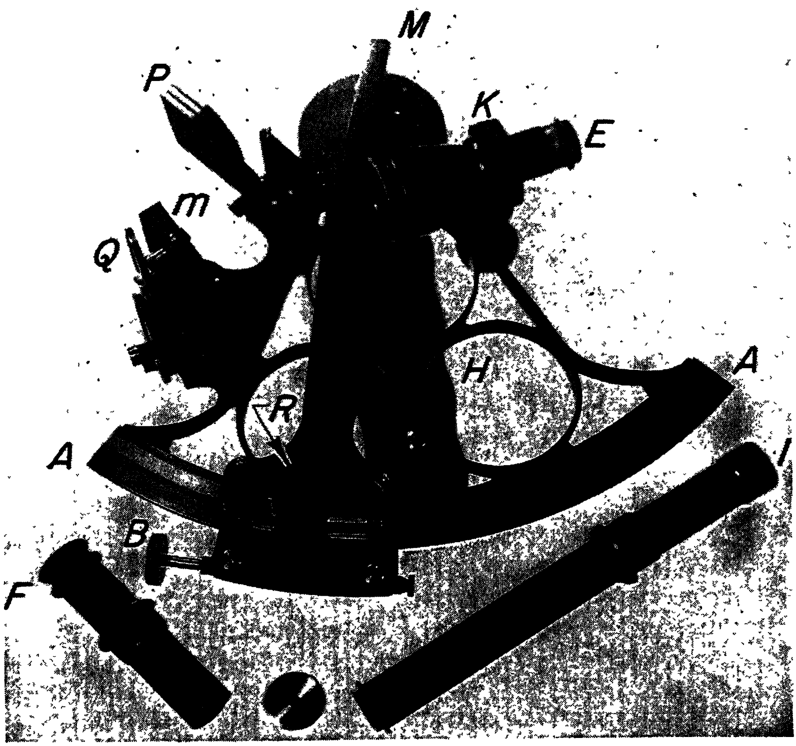


FIG. 108. The Parts of a Sextant

A common form of the marine sextant is shown in Fig. 108. The frame is of brass or some similar alloy. The graduated arc, *AA*, generally of silver, is marked in appropriate divisions; in the finer sextants, each division represents 10′, and the vernier (or micrometer) affords a means of reading to 10″. A wooden handle, *H*, is provided for holding the instrument. The index mirror, *M*, and horizon mirror, *m*, are of plate glass, and are silvered, though the upper

half of the horizon glass is left plain to allow direct rays to pass through unobstructed. To give greater distinctness to the images, a small telescope, *E*, is placed in the line of sight; it is supported in a ring, *K*, which can be moved by a screw in a direction at right angles to the plane of the sextant, thus shifting the axis of the telescope, and, therefore, the plane of reflection. This plane, however, always remains parallel to that of the instrument, the motion of the telescope being intended merely to regulate the relative brightness of the direct and reflected image. In the ring, *K*, are small screws for the purpose of adjusting the telescope by making its axis parallel with the plane of the sextant.

The vernier is carried on the end of an index bar pivoted beneath the index mirror, *M*, and thus travels along the graduated scale, affording a measure for any change of inclination of the index mirror. A reading glass, *R*, attached to the index bar, facilitates the reading of vernier and scale.

The index mirror, *M*, is attached to the head of the index bar, with its surface perpendicular to the plane of the instrument; an adjusting screw is fitted at the back to permit an adjustment to the perpendicular plane. The fixed glass, *m*, half silvered and half plain, is called the horizon glass, as it is through this that the horizon is observed in measuring altitudes of celestial bodies; it is provided with screws, by which its perpendicularity to the plane of the instrument may be adjusted. At *P* and *Q* are colored glasses of different shades which may be used separately, or in combination, to protect the eye from the intense light of the Sun.

In order to observe with accuracy and make the images come precisely in contact, a tangent screw, *B*, is fixed to the index, by means of which the latter may be moved with greater precision than by hand. This screw does not act until the index is fixed by a screw beneath the reading glass. When the index is to be moved any considerable amount, the screw is loosened; when it is brought near to its required position, the screw must be tightened, and the index may then be moved gradually by the tangent screw.

Besides the telescope, *E*, the instrument is usually provided with an inverting telescope, *I*, and a tube without lenses, *F*; also, with a cap carrying colored glasses, which may be put on the eye end of the telescope, thus dispensing with the necessity for the use of the colored shades, *P* and *Q*, and eliminating any possible error which might arise from nonparallelism of their surfaces.

The latest type of marine sextant furnished to the United States Navy is fitted with an endless tangent screw which carries a micrometer drum from which the seconds of arc are read. By pressure of the thumb the tangent screw is released and the index bar may be moved to any position on an arc by hand, where the tangent screw is again thrown into gear by releasing the pressure of the

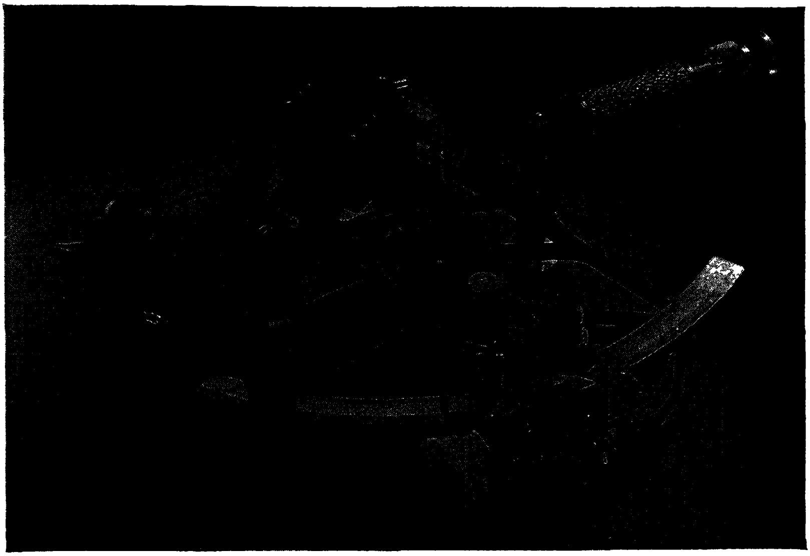


FIG. 109. Marine Sextant, with Micrometer and Bubble Attachment. Photograph from Weems System of Navigation

thumb. At night the reading of this sextant is facilitated by a small electric light carried on it and supplied by a battery contained in the handle. (See Fig. 109.)

Sextants, not fitted with micrometers, are fitted with verniers which contain one more division than the length of scale covered. Scale readings and vernier readings increase in the same direction —toward the left hand. To read any sextant, it is merely necessary to observe the scale divisions next below, or to the right of the zero of the vernier, and to add thereto the angle corresponding to that division of the vernier scale which is most nearly in exact coincidence with a division of the instrument scale.

When a ray of light is reflected from a plane surface, the angle of incidence is equal to the angle of reflection. From this it may be

proved that when a ray of light undergoes two reflections in the same plane the angle between its first and its last direction is equal

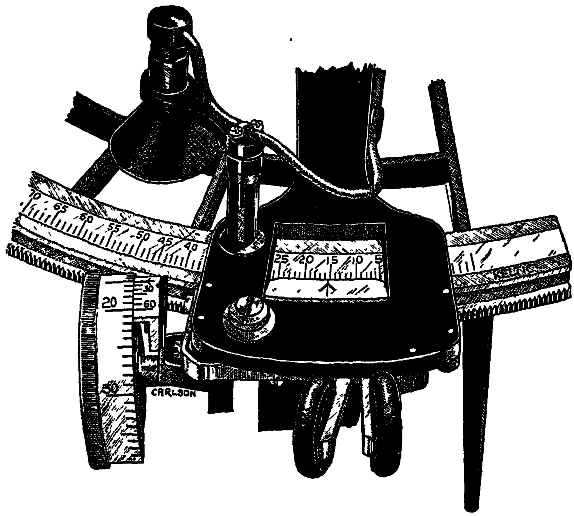


FIG. 110. Micrometer and Endless Tangent Screw of Sextant. Photograph from Weems System of Navigation

to twice the inclination of the reflecting surfaces. Upon this fact the construction of the sextant is based.

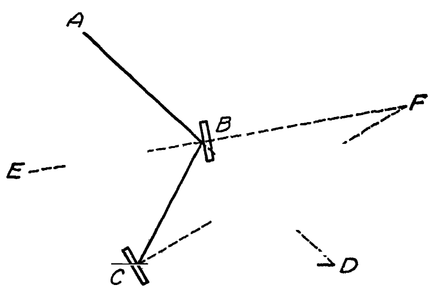


FIG. 111. The Principle of the Sextant

In Fig. 111, let *B* and *C* represent respectively the index mirror and horizon mirror of a sextant; draw *EF* perpendicular to *B*, and *CF* perpendicular to *C*; then the angle *CFB* represents the inclina-

tion of the two mirrors. Suppose a ray to proceed from A and undergo reflection at B and at C, its last direction being CD; then ADC is the angle between its first and last directions, and we desire to prove that $ADC = 2\ CFB$.

From the equality of the angles of incidence and reflection:

$$ABE = EBC, \text{ and } ABC = 2\ EBC$$
$$BCF = FCD, \text{ and } BCD = 2\ BCF.$$

From geometry:

$$BCF = ABC - BCD = 2\ (EBC - BCF) = 2\ CFB,$$

which is the relation that was to be proved.

The sextant measures angles up to 120°. The angle between the planes of the mirrors can be made 60°, or one-sixth of 360°, and the angle measured is double that between the mirrors. An *octant* is an instrument which serves the same purpose, and operates on the same principle, as the sextant, but it is capable of measuring angles only up to 90° (twice 45°, or one-eighth of 360°). Air navigators do not use the marine type sextant, but the smaller and lighter octant, which is more convenient, and sufficiently accurate for air work. They use the word "sextant," however, when referring to the octant.

An aircraft "sextant" must have some device for indicating the horizontal, as much of the time a natural horizon is not available. Gyroscopic devices, pendulum devices, and bubbles have been tried. The gyroscope is attractive theoretically, but so far these devices are too heavy and complicated for general use. The pendulum devices have not been successful as yet. Bubble type instruments have been used since 1918-1919 on aircraft, and all instruments in regular use at present are of that type. The Link bubble sextant is shown in Fig. 112.

When a bubble sextant is used on a moving ship or plane, the acceleration affects the apparent position of horizontal. The errors are not so troublesome on a ship, but at the speed of a plane they may be considerable. When a plane is flying level but accelerating rapidly, the spirit in a level is thrown to the rear, giving the apparent horizontal a dip downward toward the nose of the plane. When a plane is slowing down, the apparent horizontal dips up toward the nose of the plane. When the plane is banking, the

apparent horizontal, as measured by the bubble, should be approximately parallel to the floor of the plane, however sharp the turn. Obviously, useful observations can be made with a bubble

FIG. 112. An Aircraft Bubble Sextant in Case. Photograph from Link Aviation Devices, Inc.

sextant only when the plane is flying at a uniform speed, in a straight line, and in reasonably smooth air.

Even when flying in a straight line and at uniform speed, the bubble does not register exactly horizontal. In the chapter on motions of the Earth, you read that the rotation of the Earth deflects winds, ocean currents, and other moving objects. They are deflected to the right in the Northern Hemisphere and to the left in the Southern Hemisphere. This affects airplanes, of course, the effect

being zero at the equator, about 5′ at 400 miles per hour in latitude 40°, and about 10′ at the same speed in latitude 75°. Because of these unavoidable errors, there is no point in attempting, from an airplane, the accuracy which can be attained with a good marine sextant on board a ship.

The *American Nautical Almanac* contains the ephemerides of the Sun, and the Moon, and the planets Venus, Mars, Jupiter, and Saturn. It lists the apparent places of 55 navigational stars for the first of each month, civil time of transit at Greenwich for each of these stars, and the mean places of 110 additional stars. There are given, also, the elements and circumstances of the eclipses; a table for finding the latitude by an observed altitude of Polaris; a table of the azimuth of Polaris; tables for the interconversion of mean time and sidereal time; and tables for finding the times of rising and setting of the Sun and the Moon.

The *Almanac* contains this information for equal intervals of Greenwich civil time. Hence, before the value of any of these quantities can be found for a given local civil time or standard time, it is necessary to determine the corresponding Greenwich civil time. Should that time be one for which the *Nautical Almanac* gives the value of the required element, nothing more is necessary than to employ that value. But if the time falls between the instants specified in the *Nautical Almanac*, the required quantity must be found by interpolation. The procedure is as follows:

Take from the *Nautical Almanac*, for the nearest given preceding instant, the required quantity, together with its corresponding "hourly" or "two-hourly differences," noting the sign in each case. Multiply the "hourly difference" by the number of hours and fraction of an hour, corresponding to the interval between the time for which the quantity is given in the *Nautical Almanac* and the time for which it is required. Then apply the correction thus obtained, using the correct sign.

A modification of this rule may be adopted if the time for which the quantity is desired falls nearer a subsequent time given in the *Nautical Almanac* than it does to one preceding; in this case, the interpolation may be made backward, the sign of application of the correction being reversed.

Beginning with January 1941, the *American Air Almanac* has been issued by the Nautical Almanac Office of the U. S. Naval Observa-

tory. Previously, the *American Nautical Almanac* had been used both for surface navigation and for air navigation. Some may prefer to continue using the *Nautical Almanac*, with which they are familiar, but the *Air Almanac* is intended to replace it in air navigation. It incorporates new features designed to afford simpler and quicker results in flight, while keeping within the limits of accuracy required in the air. In order to keep it of convenient size and weight, the *Air Almanac* is issued in three sections for each year covering four months each.

The *Air Almanac* has the information for the Sun, Moon, and three planets listed on a separate page for each day. The values for a.m. are given on the front of the page, and for p.m. on the back.

The data on the page for each day are tabulated at 10-minute intervals throughout the 24 hours. Two identical tables are provided for interpolating between the 10-minute tabulations, for the exact time of observation. One of these is on a back flap, which may be inserted facing the p.m. side of the page; the other is on the inside of the front cover. It is expected that the sheets for each day will be removed from the *Air Almanac*, leaving the interpolation table on the inside of the front cover always facing the a.m. side of the page for the current day. In any case, all the data that are needed for a solution for the Sun, Moon, or a planet, may be obtained at one opening of the book. Tables for refraction and dip are on the back cover, and a table is provided on a flap inside the back cover for converting an observed altitude of Polaris into latitude.

On the a.m. side of each daily sheet, at the tops of the respective columns, appear the names and the symbols representing the Sun, Moon, and three planets. The stellar magnitudes of the planets are also indicated. Beneath each heading, the *GHA* (Greenwich hour angle) and the declination of the body is given. Column 3 tabulates the *GHA* of the vernal equinox, *GHA* ♈. This is the Greenwich sidereal time. The last column lists the parallax correction for the Moon. The plus sign is a reminder that this correction is always to be added to the sextant altitude. Near the bottom of this column are the corrections for semidiameter (S.D.) for the Sun and for the Moon. When interpolating for the *GHA* of the Moon under some conditions, a small correction is needed. This is given at the bottom of the same column, under *Corr. HA* ☾.

The diagram at the right-hand edge of the sheet shows the posi-

tions of the Moon, planets, vernal equinox, and four stars, with respect to the Sun. The Sun and Moon are represented by their conventional symbols. The planets are also identified by conventional symbols beneath the dots showing their locations. Their respective symbols are also shown adjacent to their names at the top of the page, as an aid to memory. The stars are represented by asterisks, with the letters *a*, *b*, *c*, and *d* indicating Aldebaran, Regulus, Spica, and Antares, respectively.

The diagram represents the narrow band along the ecliptic within which the Sun, Moon, and planets appear to move. The ends of the diagram are each 180° from the Sun; that is, each half of the diagram represents a complete arc across the sky, from horizon to horizon. If the diagram is held toward the southern sky, with the symbol for the Sun toward the eastern horizon (sunrise) and the west end toward the western horizon, the relative positions of the stars and planets near the time of sunrise may be visualized from the west half of the diagram. If the symbol for the Sun is held toward the western horizon (sunset), with the east end toward the east, the other half of the diagram pictures the visible planets and selected stars near the time of sunset.

On the p.m. side the tables at the right show the time of rising and setting of the Sun and Moon, and the duration of civil twilight. The last column, under the heading of *Diff.*, gives the number of minutes later that the Moon will rise or set on the following day.

The inside back cover lists the sidereal hour angle (*SHA*), right ascension (*RA*) and declination (*Dec.*) of 55 navigational stars. The Greenwich hour angle (*GHA*) of a star is obtained by adding the *GHA* of the vernal equinox ($GHA\Upsilon$), as given in the daily pages, and the *SHA* of the star, as follows:

$$GHA^* = GHA\Upsilon + SHA^*.$$

In planning his observation, it is well for the navigator to know *which heavenly bodies will be visible.* Both the *Nautical Almanac* and the *Air Almanac* have tables from which the rising and setting of the Sun and Moon can be taken. In general, both Sun and Moon are visible from soon after rising to a little before setting. For the brighter planets, and for 55 stars, the time of meridian passage at Greenwich is tabulated. Unless they are crossing the meridian quite low, they should be in good position for observation at that

time. The local mean time of crossing any other meridian is equal to the Greenwich time plus about four minutes for each degree of longitude west of Greenwich or minus four minutes for each degree of longitude east of Greenwich. To find how long before or after meridian passage a star rises or sets, the hour angle of rising or setting at that latitude can be taken from such tables as Hydrographic Office 201, or it can be read from a slide rule using the equation

$$\cos t = -\tan d \tan L$$

where t is the hour angle, d is the declination, and L is the latitude.

The approximate time of rising is obtained by subtracting the *LHA* (local hour angle) of rising from the time of meridian passage, and the approximate time of setting by adding the *LHA* (local hour angle) of setting to the time of meridian passage.

Position from Astronomical Observation. The navigator or explorer locates himself on the surface of the Earth by finding his co-

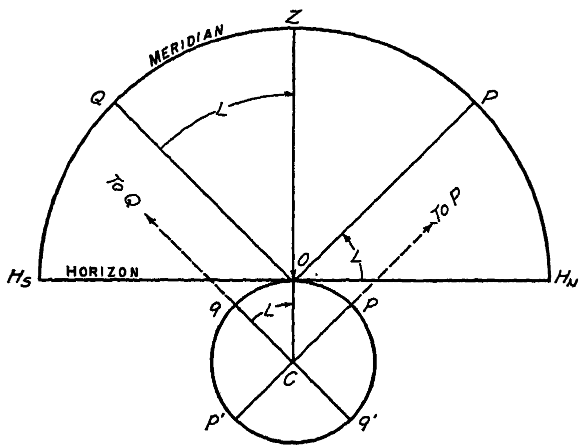


FIG. 113. Latitude Obtained from the Meridian Altitude of a Heavenly Body

ordinates, that is, his latitude and his longitude. As the problem of finding *latitude* is simpler than the problem of finding longitude, it will be taken up first.

In Fig. 113 the circle with center C represents the Earth, and the semicircle with center O represents the meridian of an observer

located at the point O. The angle qCO is equal to the latitude, L. The plane of the celestial equator is OQ and the line OP extends toward the celestial pole.

From the figure it is evident that

$$ZOQ = OCq = L, \text{ and } H_nOP + POZ = 90°$$

where H_n is the north point of the horizon. But

$$ZOQ + POZ = 90°.$$

Hence,

$$H_nOP = QOZ = OCq = L.$$

The last equation gives the two fundamental relations for latitude. It states that the latitude of the observer is equal to (1) the declination of the observer's zenith and (2) the altitude of the north celestial pole.

Let the latitude, L, be considered plus north, the declination, d, be considered plus north, and the zenith distance, z, be considered

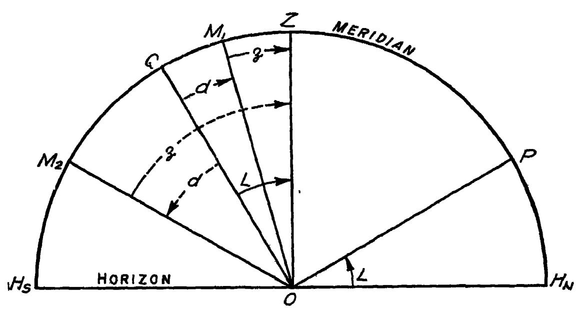


FIG. 114. Latitude from a Meridian Altitude, Above or Below the Celestial Equator

plus south. Suppose, further, that a heavenly body is south of the zenith, in a north latitude. (See Fig. 114.) If it is in the position M_1, between the celestial equator and the zenith, it is evident that

$$L = d + z.$$

If it is below the celestial equator, the declination, d, is negative,

and the equation still holds. From similar figures, it is seen that this equation holds for all latitudes, zenith distances, and declinations either north or south.

If an object can be observed on the meridian, the latitude is determined easily by the above equation whether the object be the Sun, the Moon, a planet, or a bright star. The star Polaris is never far from the meridian, and the reduction for *latitude* of an observation made on *Polaris* at any time is relatively simple.

As has been stated, the altitude of the celestial pole is equal to the latitude of the place from which it is observed. Polaris is not exactly at the pole, but moves about it in a small circle with a radius of about 1° 2.'5. Now if the altitude of the pole is equal to the latitude, it is apparent that when Polaris is directly above the pole the radius of 1° 2.'5 must be subtracted from the altitude of Polaris to obtain the altitude of the pole, or the latitude of the place. If the star is directly below the pole, the radius of 1° 2.'5 must be added to the altitude of the star in order to obtain the latitude. If the star is directly to the right or to the left of the pole, the altitude of the star is the same as the altitude of the pole, or the latitude.

In the *Air Almanac* there is a special table (on flap inside back cover) giving the correction to be applied to an observed altitude of Polaris for various values of the local sidereal time ($LHA\Upsilon$) in arc. Table I in the *Nautical Almanac* gives the correction for various values of the local sidereal time, in time units. Table III in the *Nautical Almanac* gives the correction for various values of the local hour angle of Polaris.

The local sidereal time can be obtained readily from the Greenwich sidereal time and the longitude. The Greenwich sidereal time may be read from a watch directly, or taken from the *Air Almanac* for the proper value of the Greenwich civil time. If Table III in the *Nautical Almanac* is used, the Greenwich hour angle of Polaris might be figured from tables in the same almanac, and the longitude subtracted to obtain the local hour angle. The latitude is obtained by taking the correction from the table and applying it to the observed altitude.

The *longitude*, as you have read, is determined from the equation:

$$Lo = T_G - T$$

where Lo is the longitude west, T_G is the Greenwich time, and T the local time.

For the Sun, the hour angle is equal to the apparent solar time (astronomical), and since the equation holds for any time, including apparent, it can be written

$$Lo = GHA\ (\text{Sun}) - LHA\ (\text{Sun}).$$

For a star, the sidereal time is equal to the hour angle plus the

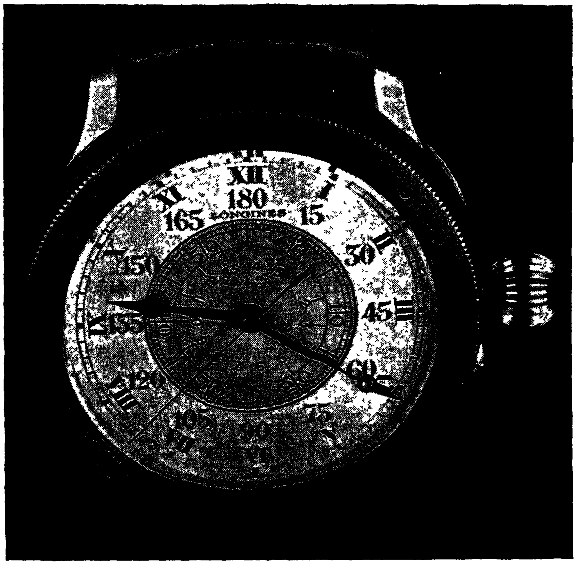


FIG. 115. A Navigational Watch Reading Hour Angle Directly. Photograph from Weems System of Navigation

right ascension, that is $LST = HA + RA$. Making this substitution for sidereal time in the fundamental equation for longitude, we have

$$Lo = (RA + GHA) - (RA + LHA).$$

If the parentheses are removed, the right ascension, RA, cancels out and the equation becomes

$$Lo = GHA - LHA.$$

Hence, longitudes can be obtained just as readily from the difference of hour angles as from the difference of time. If the Greenwich

hour angles are tabulated in arc, so that they can be taken out for any instant of civil time, longitude can be obtained by observing the local hour angle, and subtracting that from the Greenwich. For this work, the Greenwich hour angle is tabulated in the *Nautical Almanac* and in the *Air Almanac*, for the Sun, Moon, the brighter planets, and the brighter stars.

The determination of longitude is most simple when an object can be observed on the meridian since the local hour angle of the Sun, or other heavenly body, on the meridian is zero. In this case the longitude is simply the Greenwich hour angle in arc.

In navigational work, however, the time an object passes the meridian cannot be observed with accuracy, in general. If an observer is stationed on land, he can determine the time of meridian passage indirectly with a sextant by noting when a certain altitude is reached in the eastern sky, and when the same altitude is reached in the western sky.

The navigator, however, whether he be on a ship or in an airplane, is moving, and the method of equal altitudes cannot be used. From the triangle formed by the zenith, the pole, and the heavenly body, the hour angle must be calculated to obtain the longitude. The three sides of this triangle are, $90° - d$, $90° - h$, and $90° - L$. The declination, d, can be taken from either almanac, and the altitude, h, is observed, but a third quantity, the third side, or one of the angles, must be known before the triangle can be solved. There are several possibilities.

One method is the timing of the passage of a known star through the zenith. This method is used at the U. S. Naval Observatory where stars are photographed on a moving plate as they pass the zenith. Of course, no stars pass the zenith exactly, but a considerable number pass near enough to be photographed with an instrument pointed at the zenith. These stars give quite accurately the declination of the zenith, which is the latitude, and the right ascension of the center of the plate, which is the local sidereal time at which the center of the plate passes the meridian. If an instrument could be devised for observing stars near the zenith from a ship or from a large airplane, the determination of longitude and latitude would be simplified. The declination of the zenith would be the latitude and the Greenwich hour angle of stars passing the zenith

would be the longitude. It would be unnecessary to solve the astronomical triangle. No such instrument has been devised as yet, however.

As a second possibility, one might imagine an instrument similar to the theodolite with which both the altitude and the azimuth of a heavenly body could be observed. With such an instrument, the observation of a single heavenly body would give three parts of the astronomical triangle referred to in a preceding paragraph. The declination, taken from either almanac, gives the side $90° - d$, the observed altitude gives the side $90° - h$, and the azimuth observed by such an instrument would give the angle opposite the side $90° - d$. With the three parts known it would be possible to solve for the hour angle and for the side $90° - L$. From the Greenwich hour angle and the local hour angle the longitude is obtained, and from $90° - L$ the latitude, L, is obtained. This method could be used now, but the results would be weak, since the azimuth depends on the compass and cannot be observed with sufficient accuracy.

The third possibility for obtaining both the longitude and latitude by observation is the observation of two altitudes, preferably observed almost simultaneously, and of two different heavenly bodies. By day it can be the Sun and the Moon. By night it can be two stars in different parts of the sky. These observations of altitude give two equations of the form

$$\cos t = \sin h \sec d \sec L - \tan d \tan L.$$

Since $t = LHA = GHA - Lo$, the equation becomes

$$\cos (GHA - Lo) = \sin h \sec d \sec L - \tan d \tan L.$$

Each observation gives an equation of this form with GHA, h, and d known. Hence in the two equations the only unknowns are the longitudes Lo and the latitudes L. Hence, the two equations in the two unknowns can be solved, and the solution is usually made graphically. Sumner's method discussed in the next paragraphs is essentially a graphical solution of the two equations in two unknowns, the observer's longitude and the observer's latitude.

The method of navigation involving the use of the *Sumner line* takes its name from Capt. Thomas H. Sumner, an American ship-

master, who discovered and published it. As a proof of its value, the incident which led to its discovery may be related:

"Having sailed from Charleston, S. C., 25th November, 1837, bound for Greenock, a series of heavy gales from the westward promised a quick passage; after passing the Azores the wind prevailed from the southward, with thick weather; after passing longitude 21° W. no observation was had until near the land, but soundings were had not far, as was supposed, from the bank. The weather was now more boisterous and very thick, and the wind still southerly; arriving about midnight, 17th December, within 40 miles, by dead reckoning, of Tuskar light, the wind hauled SE. true, making the Irish coast a lee shore; the ship was then kept close to the wind and several tacks made to preserve her position as nearly as possible until daylight, when, *nothing being in sight*, she was kept on ENE. under short sail with heavy gales. At about 10:00 a.m. an altitude of the Sun was observed and the chronometer time noted; but, having run so far without observation, it was plain the latitude by dead reckoning was liable to be in error and could not be entirely relied upon.

"The longitude by chronometer was determined, using this uncertain latitude, and it was found to be 15′ E. of the position by dead reckoning; a second latitude was then assumed 10′ north of that by dead reckoning, and toward the danger, giving a position 27 miles ENE. of the former position; a third latitude was assumed 10′ farther north, and still toward the danger, giving a third position ENE. of the second 27 miles. Upon plotting these three positions on the chart, they were seen to be in a straight line, and this line passed through Small's light.

"It then at once appeared that the observed altitude must have happened at all the three points and at Small's light and at the ship at the same instant."

Then followed the conclusion that, although the absolute position of the ship was uncertain, she must be somewhere on that line. The ship was kept on the course ENE, and in less than an hour Small's light was made, bearing ENE ½ E and close aboard.

The latitude by dead reckoning was found to be 8′ in error, and if the position given by that latitude had been assumed correct, the error would have been 8 miles too far south, and 31′ 30″ of longitude too far west, and the result to the ship might have been dis-

astrous had this wrong position been adopted. This represents one of the practical applications of the Sumner line.

You read earlier that the Sumner method was, in effect, a graphical solution of two equations in two unknowns. The solution will be understood better if the curve represented by the equation is known. Suppose that Polaris were exactly over the North Pole. To an observer at that point its altitude, or angle of elevation above the horizon, would be 90°, or exactly at the zenith. Now if the observer moved southward for a distance of 10°, to latitude 80°, the altitude of the star would be found to be 80°; from any point on this parallel, whether toward Asia, or toward North America, the altitude is the same. All points at which the altitude of Polaris is 80° must be located somewhere on that circle, and nowhere else. The 80° parallel may therefore be called a circle of position.

Similarly, from any point in latitude 30°, with the observer 60° from the pole, the altitude would be 30° and the 30° parallel is another circle of position; and so on until at the equator, with the observer 90° from the pole, the altitude of the star would be 0°, and the equator would be the farthest circle from which the star is visible.

From the foregoing it can be seen that for Polaris the point directly beneath the star is the center of a system of concentric circles of position. From every point on any given circle the altitude of the star is the same. As the observer moves away from the point directly beneath the star, there is a decrease in the altitude of the star proportional to the distance moved; if away a distance equal to 1′ of latitude, the altitude decreases 1′; if away 10° farther, the altitude decreases another 10°, and so on. In each instance the radius of the circle of position (that is, the distance of the observer from the point beneath the star) is equal to 90° minus the observed altitude.

These principles hold true not only for a star directly over the pole, but for all stars. One can imagine a series of concentric circles centered on the point where the star is seen in the zenith, and the relation between the observed altitude and the corresponding circle of position would still hold. Evidently, the smaller the altitude observed, the greater the distance from the point on the Earth directly beneath the star.

Through long familiarity with latitude, it has become customary

to measure distances along a meridian, north and south, in terms of degrees and minutes. One does not usually think of distances in other directions in these terms, however, yet great-circle distances, the shortest distance between points on a globe (see Fig. 116), in any direction are always computed in degrees and minutes, and

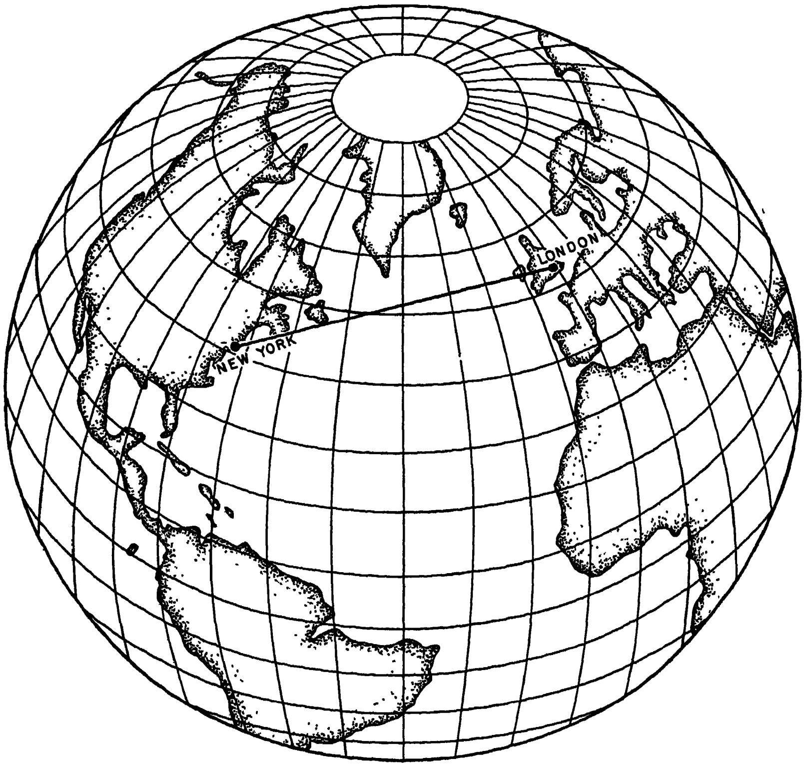


FIG. 116. A Great Circle Distance, the Shortest on a Globe

then converted into nautical miles, statute miles, meters, or other desired units. A chart may have a scale of distances in terms of degrees and minutes of a great circle, just as it has a scale of distances in terms of statute or nautical miles. If a small scale chart were provided with such a scale, it would be possible to plot on the chart from the *Air Almanac* the position beneath any star at the instant of observation. With that point as a center, the circle of posi-

tion could be drawn with a radius equal to 90° minus the observed altitude, with no computations whatever.

We have seen that the observed altitude of a star definitely determines a circle of position at a known distance from the point beneath the star. If at the same time and place, the altitude of a second star is observed, a second circle of position is determined, and, since the observer is on both circles, he must be at a point where the two intersect. The positions of the stars Vega and Alphecca, plotted for the moment of observation on a chart from data in the *Air Almanac*, are shown in Fig. 117. Then with radius equal to 90°, minus the

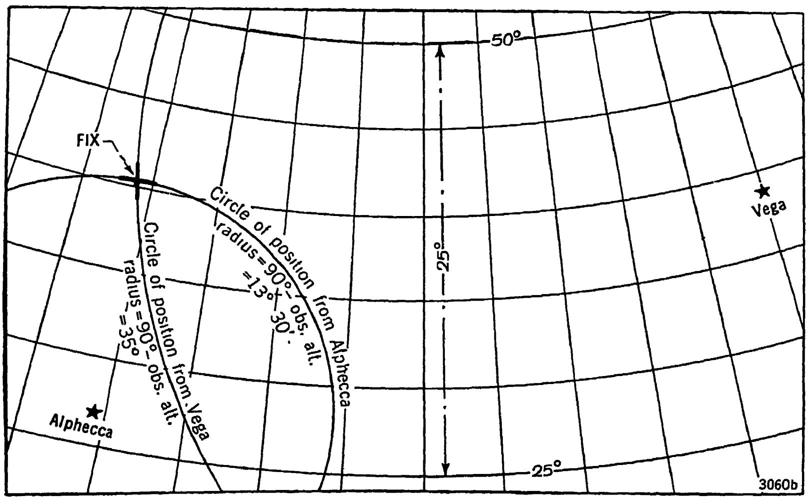


FIG. 117. A Fix from Two Circles of Position

observed altitude in each case, the two circles of position were drawn, determining the observer's position as shown.

From the figure it may be seen that the two circles of position would also intersect just outside the southern border of the chart. For every pair of intersecting circles there must be two points of intersection, but this is not confusing in practice. The two points are nearly always far enough apart that one of them may be dismissed as impossible. In the case illustrated, the poorest navigator, somewhere in Nevada, should be able to know at once that he was not in Mexico, 1,500 miles away.

where

$$S = \tfrac{1}{2}(h + L + P), \text{ and } P = 90° - d.$$

The function $\sin^2 \tfrac{1}{2} t$ is known as haversine t, and Bowditch includes tables for that function.

A formula which is more simple, and is usually accurate enough, is the one already given,

$$\cos t = \sin h \sec d \sec L - \tan d \tan L.$$

This formula is convenient when a slide rule is used for the solution.

A trigonometric solution takes time, and to save the time of the navigator, Hydrographic Office tables H.O. 203 and H.O. 204 were published in 1923 and 1925, respectively. Using these tables, a navigator assumes a latitude, and with that and the observed altitude, the hour angle can be taken out and the longitude obtained from this. It is customary to assume two integral degree values for the latitude, and obtain the two corresponding longitudes. For each observation this gives two points on the line of position, which can be plotted and connected by a straight line. The intersection of the two lines is the "fix," or position. Simplifications have more recently been developed in the form of newer tables. Among the most recent and efficient are the Hydrographic Office tables H.O. 211 and H.O. 214.

Probably the simplest method is that of the *Star Altitude Curves*, published by the Weems System of Navigation. As you have read, the right ascensions and declinations of the stars change very slowly. Hence, for some years a star can be considered as at the zenith of the same point on the Earth at a given moment of Greenwich sidereal time. For any one place and any one sidereal time the circles of position of a star remain essentially the same for several years. The Weems curves were constructed for various stars and various altitudes, using the tables H.O. 203 and H.O. 204. The intersecting circles of position for three stars are printed on the same graph (Mercator) in different colors.

In determining a position by this method the altitudes of two of the stars for which the curves have been drawn are observed in quick succession, and the Greenwich sidereal time of the observations recorded. (See Fig. 119.) Then the point of intersection of

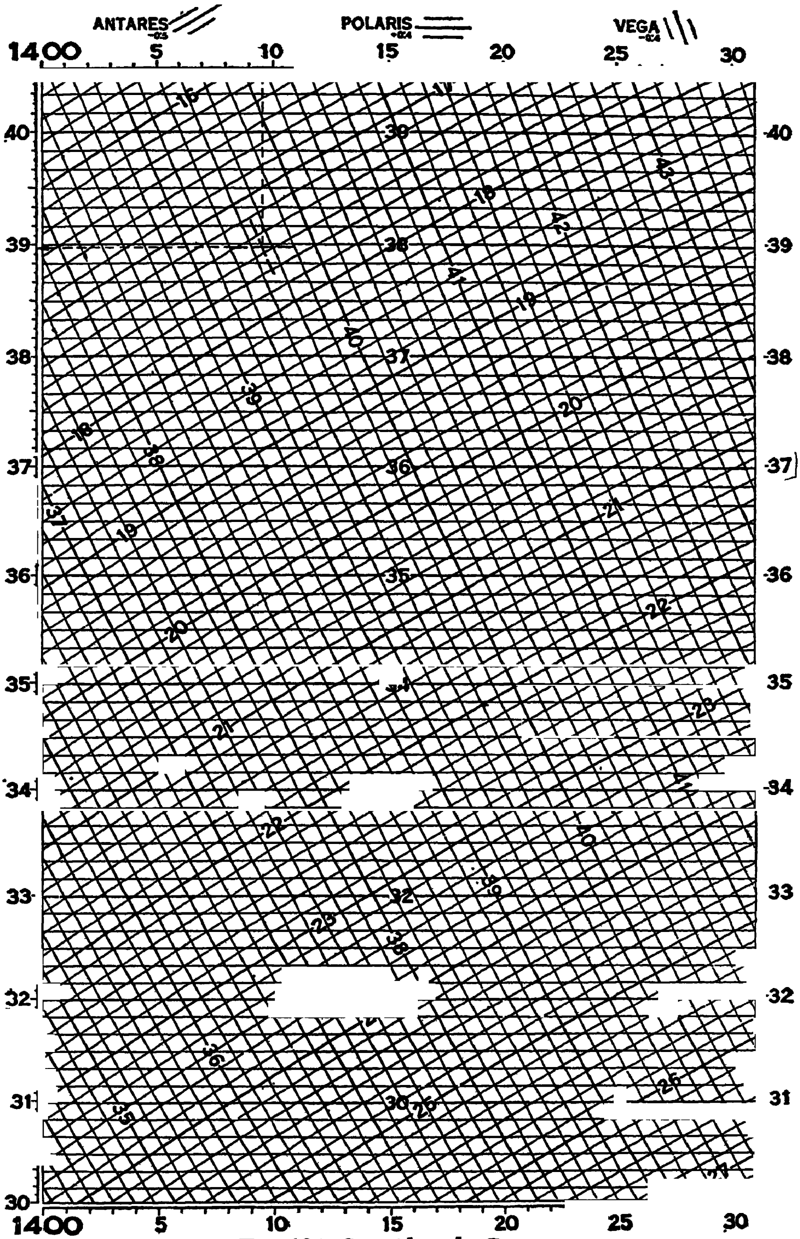


Fig. 120. Star Altitude Curves

the curves corresponding to the altitudes observed is noted, and read from the margins of the graph the latitude of the observer's position and the local sidereal time at that place. Combined with the Greenwich sidereal time by ordinary arithmetic, the local sidereal time gives the longitude in terms of time. This may be converted to arc by means of a special table in the *Air Almanac*. The position has thus been fixed with a minimum of time and almost no arithmetic.

This method is subject to the disadvantage that it cannot be used by day and is available for relatively few stars at night. For good results, not more than a minute should elapse between the two altitude observations; if more time does elapse, a method is provided for carrying forward the curve corresponding to the first observation. It has the advantage, however, of being the fastest of present methods, and its accuracy is quite sufficient for the purposes of air navigation. Still another advantage is that, if a watch running on Greenwich sidereal time is carried, the almanac need not be used in the reduction. The method can be illustrated by the following problem.

On November 17, 1942, at Greenwich sidereal time $19^h\ 15^m\ 29^s$, the altitude of Vega was observed to be 39° 35′, and immediately thereafter the altitude of Polaris was observed to be 37° 58′.

The solution is as follows: On the proper page of the Weems *Star Altitude Curves* the curve for the measured altitude of Vega is drawn in, and also that for Polaris. The short portions necessary are drawn as dotted lines near the intersection. (See upper left-hand corner of Fig. 120.) Then from the intersection, vertical and horizontal dotted lines are drawn to the scales on the margin. Notice that the Polaris lines are nearly, but not exactly, horizontal. From the left margin, the latitude is read as 38° 58′. From the top margin, the local sidereal time is read as $14^h\ 9\overset{m}{.}6$, or $14^h\ 9^m\ 36^s$ approximately. Subtracting this from the Greenwich sidereal time, $19^h\ 15^m\ 29^s$, gives $5^h\ 5^m\ 53^s$ as the longitude west. Converting to arc, this becomes 76° 28′.2 W.

Exercises

1. How closely should a navigator on an airplane expect to fix his position? How closely should a navigator on a ship expect to fix his position?
2. What are the most important corrections to the observed altitude to give the true altitude?
3. What is the refraction correction if the temperature is 36° F, the barometer reads 29.47 inches, and the altitude of the star is measured as 54° 30′?
4. Considering the distance of the Moon 240,000 miles and the radius of the Earth 4000 miles, find the difference in position of the Moon as observed from latitudes + 30° and − 30°, when it is overhead at the equator.
5. What is the essential equipment for the navigator?
6. Identify and explain the parts of a sextant.
7. What errors must be avoided, or corrected for, when using a bubble sextant in flight?
8. Tabulate the time of Greenwich meridian passage for August 4, 1943, at latitude 40° N of Vega, Aldebaran, and Mars. (Take from *Nautical Almanac.*)
9. When are the following counted plus and when minus: latitude, declination, zenith distance, local hour angle, and longitude?
10. If the Greenwich civil time of local mean noon is 18:46:37, what is the longitude?
11. Explain the equal altitudes method of longitude determination.
12. If an observer times the Sun in the eastern sky at altitude 36° 56′ 42″ as 9:56:34 a.m. central standard time, and at the same altitude in the western sky at 2:31:47 p.m. central standard time, what is the longitude?
13. What different types of observations may be used to obtain the longitude and latitude?
14. Using the formula on page 272, calculate the local hour angle for the following data: (A slide rule is sufficiently accurate for this purpose.)

latitude	declination	altitude
10°N	9°N	26°E
26°S	24°N	39°W
51°N	17°N	10°E
42°S	21°S	28° 30′W

15. Using the local hour angles from problem 14, and a Greenwich civil time of $17^h\ 29^m\ 30^s$, find the corresponding longitudes.
16. At Greenwich civil time, June 1, 1943, 3^h: 38^m: 00^s, Vega was observed in the east at 40° 44′ altitude and Antares was observed in the southeast at 20° 37′ altitude. The dead reckoning position was longitude 87° 30′ west and latitude 30° 30′ north. Find the correct longitude and latitude.
17. Draw a diagram similar to Fig. 114, page 261, using a star which is north of the zenith to show the derivation for the formula $L = z + d$.

☆ XIII ☆

The Moon

The Moon was an object of worship for early people, and it has been the subject of much study by modern astronomers. Next to the Sun it is the most conspicuous and important of the heavenly bodies, but its importance is due solely to its nearness. The Moon is, except for meteors, the smallest of the heavenly bodies visible to the naked eye.

The Moon is the Earth's attendant or *satellite*; that is, the Moon goes around the Earth as the Earth goes around the Sun. The Earth has only one satellite, but several of the planets have more—Saturn has nine and Jupiter has eleven.

In spite of the smallness of the Moon it is nearer the size of the Earth than any other satellite in the solar system is to the size of the planet about which it revolves. No satellite of another planet can be seen from the Earth without a telescope, but from the nearer planets the Moon, as well as the Earth, could be seen easily with the naked eye. The Earth and the Moon would appear as twin planets, rather than as planet and satellite.

The Earth and Moon Seen from Venus. From Venus, the Earth would appear about as much brighter than Venus does to us as Venus is brighter than Jupiter for us. The Moon would be about as bright as Jupiter is for us. The greatest distance of the Moon from the Earth, as seen from Venus, would be about half a degree, or a little less than the distance across the bowl of the dipper figure in the Pleiades.

The Moon is a dark body, which shines only by reflected sunlight. The bright portion is that upon which the Sun is shining. The *phases* of the Moon are the changes in appearance of this bright portion as the Moon goes around the Earth.

The Phases of the Moon. At *new* Moon, as it is given in the calendar, the Moon sets with the Sun. (See Fig. 121.) The dark side of the Moon is toward us, and so the Moon is not visible unless there is an eclipse of the Sun.

A quarter of a lunar month later, the Moon is at *first quarter* and is on the meridian, or due south, at sunset. At first quarter, exactly half of the face of the Moon is bright. Note that the quarter Moon is not a crescent as some people erroneously believe. After

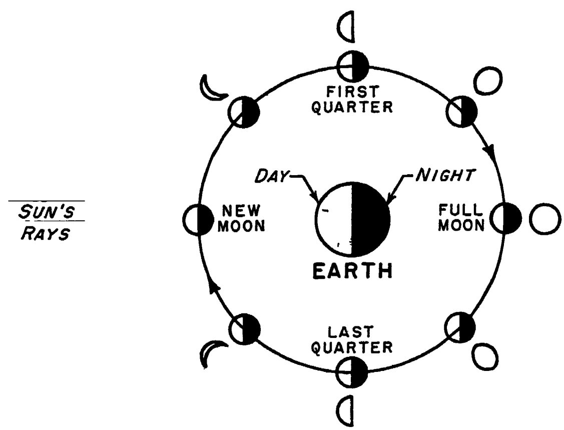


FIG. 121. The Phases of the Moon

another quarter of a month, the Moon is *full*, and it is rising at sunset. The entire face of the Moon is bright. After another quarter of a month the Moon is at *last quarter*. It rises at about midnight and is due south at sunrise. Half of the face of the Moon again is bright. Between first quarter and full, and again between full and last quarter, when more than half of the Moon's face is bright, the phase is termed *gibbous*.

Two or three days after new Moon, the Moon can be seen as a bright crescent in the western sky when the stars are appearing in the twilight. In addition to the bright crescent illuminated by sunlight, the remainder of the face of the Moon is illuminated more faintly, but is distinctly visible. This fainter illumination of the portion not in sunlight is due to light reflected by the Earth, or *earthshine*. As we see this crescent Moon low in the west just after

sunset, the Pacific Ocean is in full sunlight and is reflecting light back on the Moon.

When we on the Earth see the crescent new Moon, the Moon is nearly on a line between the Earth and the Sun, and for the Moon

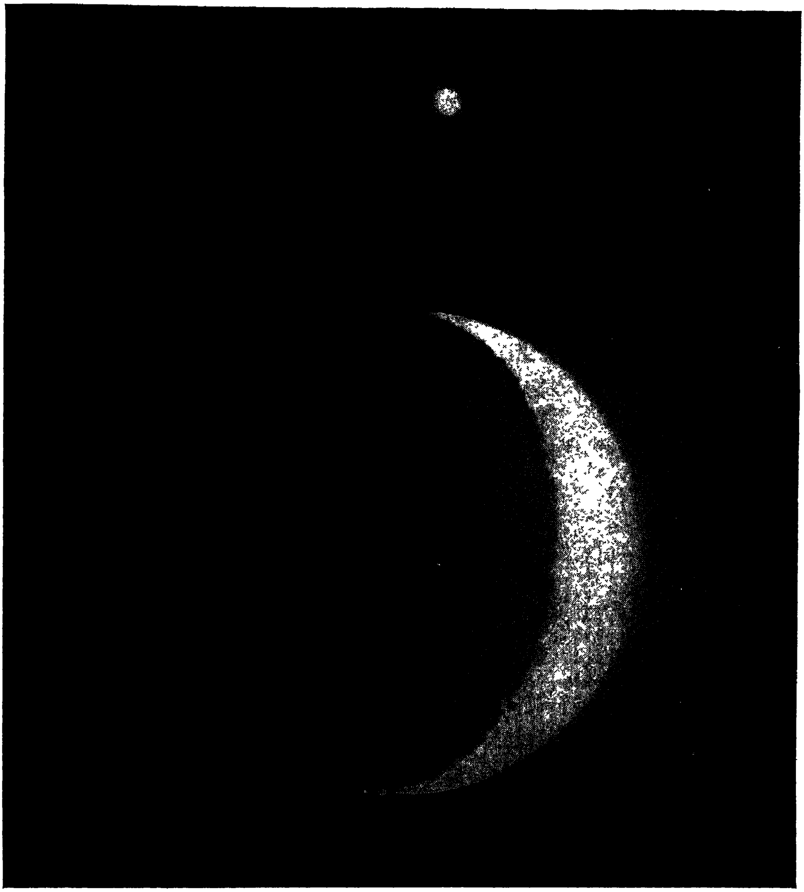


FIG. 122. Earthshine on the Moon, and a Conjunction of the Moon with Venus. Photograph from Lowell Observatory

the Earth is almost full. When we on the Earth see the Moon in the quarter phase, the Earth is in the quarter phase for the Moon. At this phase there still is sufficient earthshine on the Moon for us to see the portion of the Moon not in sunlight, but as the Moon

passes from quarter toward full, the sunlit portion gives us more light, and the earthshine becomes fainter until invisible.

The horns, or *cusps*, of the crescent Moon must point away from the Sun. In early Spring, the crescent new Moon lies rather flat. In early Autumn, the crescent new Moon is tipped up, standing on one cusp. As the Moon is much closer than the stars or planets, no star or planet can be seen projected on the face of the Moon. There are stories, especially in fiction, of seeing stars inside the horns of the Moon, but it has been known since classical times that such a thing is impossible.

The Brightness of Moonlight. From visual estimates, which are difficult, it has been calculated that it would take 450,000 full moons to give as much light as the Sun. Photoelectric work at the Harvard Observatory indicated that the Moon is a little brighter relatively than the earlier visual work had indicated. The Harvard result was that 385,000 full moons would equal the light of the Sun. The magnitude of the full Moon is −12, and of the quarter Moon is −10.

The Apparent Path of the Moon. As the Moon goes around the Earth, its path in the sky follows the ecliptic rather closely. The Sun goes around the ecliptic in a year, but the Moon goes around in a month. In a month the Moon goes all the way round from new Moon to new Moon with an eastward motion of about 13° per day, which means that it crosses the meridian on the average, 50½ minutes later each day. In addition to its eastward motion it also moves north and south about as much as the Sun does in a year. At some time each month the Moon will be rising in the southeast and going across the southern sky rather low and setting in the southwest, like the late December Sun. About two weeks later the Moon will be rising in the northeast, passing nearly overhead, and setting in the northwest like the late June Sun. People notice the Moon most when it is near full because it is rising at sunset and shining brightly all night.

During any one night between rising and setting the path of the full Moon across the sky is about the same as the Sun's path during the day six months earlier. The full Moon is opposite the Sun, and when the Sun sets in the southwest, as in December, the full Moon must rise in the northeast, like the Sun in June. Also, at a given hour of night, the Moon is about where the Sun was at that hour of the day six months earlier. The winter full Moon at ten o'clock at

night is where the summer Sun is at ten o'clock in the morning, and the winter full Moon at midnight is high in the south, like the summer Sun at noon.

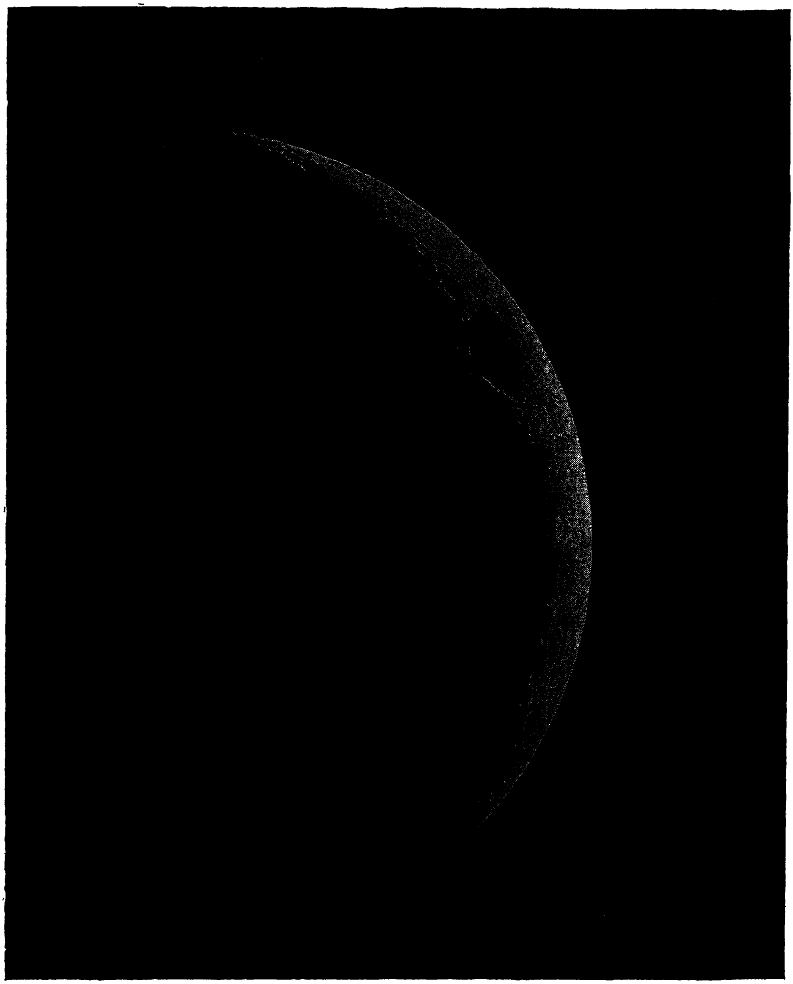


FIG. 123. The Crescent New Moon (Age 3.85 Days). Photograph from Yerkes Observatory and University of Chicago Press

The Sun gives us the most light and heat in late June, hence the full Moon should give us the most light in late December. The

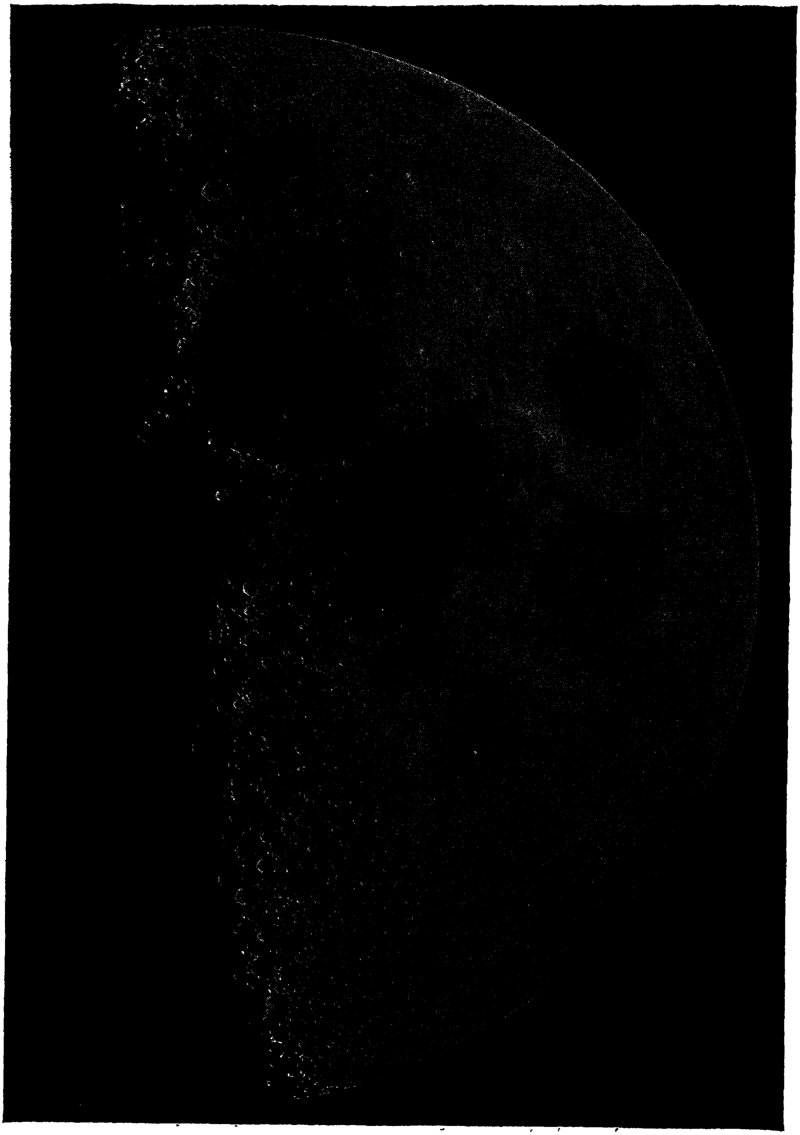


FIG. 123A. The Moon at First Quarter. Photograph from Yerkes Observatory and University of Chicago Press

brightness of the late December full Moon is increased a little by the fact that the Earth is closest to the Sun at that time, bringing the Moon also closer to the Sun, hence making it brighter.

Another interesting full Moon is the one nearest the autumn equinox in September. This is called the *harvest Moon,* because it comes near the time of harvest in the latitude of northern Europe and Canada. Remembering that the full Moon is opposite the Sun, the harvest Moon in its rising and setting corresponds to rising and setting of the Sun near the spring equinox. The Sun is then moving north rapidly from day to day. Hence from night to night, the late September full Moon moves north rapidly. Its motion from one night to the next is as much as the northward motion of the March Sun in twelve or thirteen days. This means that instead of rising fifty minutes later from night to night, as it does on the average, the harvest full Moon, in latitude 40°, rises only about twenty minutes later, and in northern Europe, the delay in rising may be five minutes, or even less.

At the time of the harvest, for several evenings in succession, a nearly full Moon will be shining before the end of twilight. This is a great convenience for people who want to continue working in the fields after sundown. The October full Moon, which shows the same effect to a smaller extent, is called the *hunter's Moon.*

The Distance of the Moon. The Greek astronomer Ptolemy, living in Alexandria about 150 A.D., computed that the distance of the Moon from the Earth equaled 59 times the radius of the Earth. Using a modern figure for the radius of the Earth, this gives 233,000 miles for the distance of the Moon instead of the more correct 239,000 miles. The modern figures for the distances of the Moon are: least, 221,000 miles; greatest, 253,000 miles; and mean, 239,000 miles. Often it is rounded off as 240,000 miles, where accuracy is not essential.

The distance from the Earth to the Moon is determined by sighting it at the same time from two distant points on the surface of the Earth. The Moon is so close that sighting from these points shows it in a different position among the stars, just as sighting, first with one eye and then with the other, on a lead pencil held at arm's length causes it to appear in different positions against the wall of the room. The Moon might be observed from Copenhagen, Denmark, and from Capetown, South Africa, simultaneously.

Copenhagen corresponds to one eye of the observer, Capetown to the other, the Moon to the pencil, and the stars to the wall of the

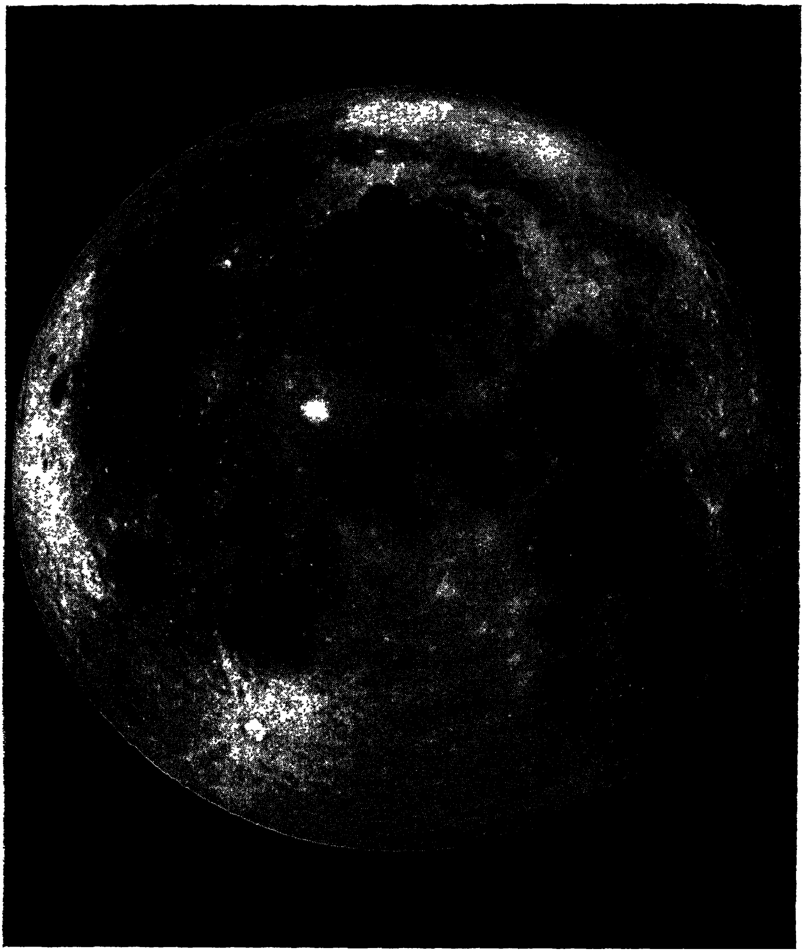


FIG. 124. The Full Moon. Photograph from Yerkes Observatory and University of Chicago Press

room. The shifting of the Moon is enough so that the displacement can be measured, without optical aid, with an uncertainty of only seven per cent or less.

The difference in direction of an object as viewed from two dif-

ferent places is known as its *parallax.* For the Moon, and the other bodies in our solar system, the positions are calculated as they would be seen from the center of the Earth. A person who sees the

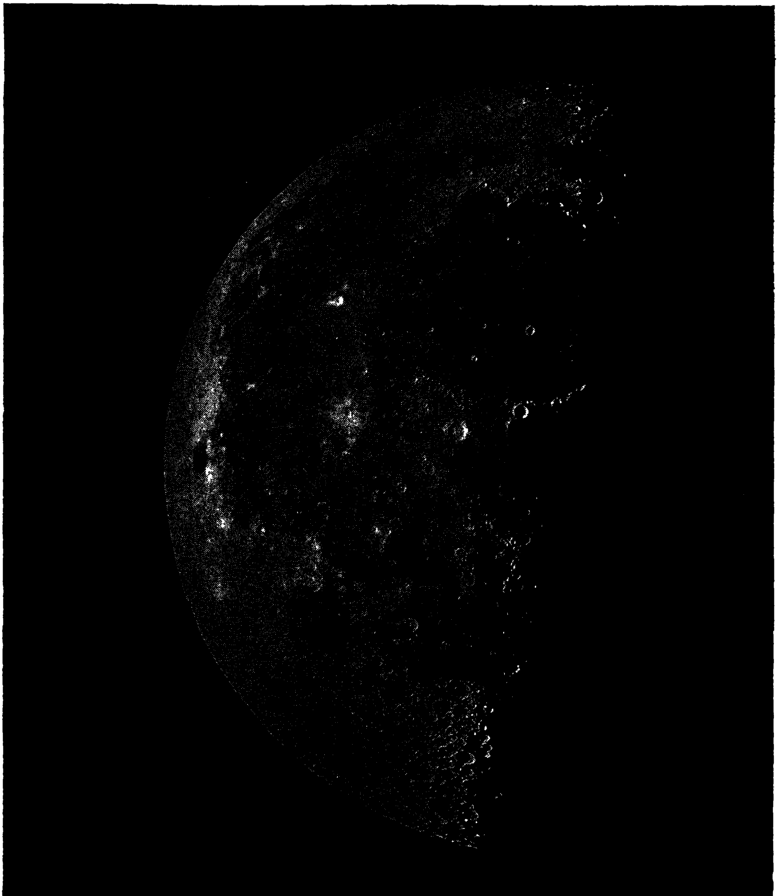


FIG. 125. The Moon at Last Quarter. Photograph from Yerkes Observatory and University of Chicago Press

Moon overhead sees the Moon in its calculated position among the stars, since he is on a line from the Moon to the center of the Earth. A person who sees the Moon on the horizon is nearly four thousand miles, and as far as possible, from this line. He sees the

greatest possible displacement or parallax, a little less than one degree when the Moon is at average distance.

The Orbit of the Moon. You have read that the Earth's orbit about the Sun is an ellipse with the Sun at one focus. The Moon moves about the Earth as the Earth moves about the Sun. The Moon's orbit is an ellipse with the Earth at one focus. The nearest point of the orbit (distance about 221,000 miles) is termed *perigee.* The farthest point (distance about 253,000 miles) is termed *apogee.*

Size and Mass of the Moon. The diameter of the Moon is 2160 miles, or slightly more than one-fourth the diameter of the Earth. The mass of the Earth is about 81.5 times the mass of the Moon, that is, the Moon's mass is about 1/82 that of the Earth. Since the volume is 1/49 that of the Earth, but the mass only 1/82, it is evident that the Moon must be made of lighter material than the Earth.

The law of gravitation (page 321) states that

$$F = \frac{m_1 m_2}{d^2} K$$

where K is the universal constant of gravitation, the numerical value of which depends on the units employed.

Let G be the gravitational pull on a unit particle at the surface of the Earth, and g the gravitational pull on a unit particle at the surface of the Moon. Then, for the Earth,

$$F = G,\ m_1 = E,\ m_2 = 1, \text{ and } d = 3950 \text{ miles.}$$

For the Moon,

$$F = g,\ m_1 = E/81.5,\ m_2 = 1, \text{ and } d = 1080 \text{ miles.}$$

Whence

$$G = \frac{E}{3950^2} K,\ g = \frac{E}{81.5 \times 1080^2} K.$$

Whence the ratio of the two pulls is

$$(g/G) = \frac{3950^2}{1080^2 \times 81.5} = 0.164, \text{ or approximately } 1/6.$$

We find that gravity at the surface of the Moon is about one-sixth

that at the surface of the Earth. A man weighing 180 pounds on the Earth would weigh about 30 pounds on the Moon, by a spring balance. He would be able to jump about six times as far and as high as on the Earth.

Center of Gravity of the Earth-Moon System. We speak about the Moon going about the Earth, but, more accurately, both Earth and Moon go around a common center of gravity. The center of gravity for the Earth-Moon system is 2900 miles from the center of the Earth, which places it within the Earth. For ordinary purposes we can say that the Moon goes around the Earth, but in accurate work astronomers must use the center of gravity of the system.

Path of Moon with Respect to Sun. As the Moon moves around the Earth in its orbit, its velocity with respect to the Earth is not

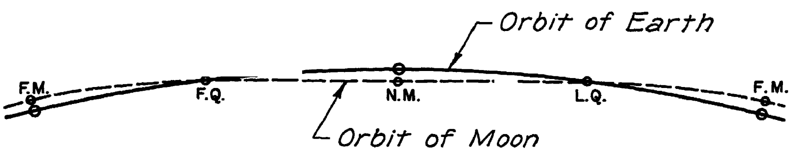


FIG. 126. Deviation of the Moon from the Earth's Orbit

quite two-thirds of a mile per second. The velocity of the Earth about the Sun, carrying the Moon with it, is 18½ miles per second. Obviously, much the greater part of the motion of the Moon is about the Sun, and the Moon deviates by a relatively small amount from the orbit of the Earth. Though the path of the Moon is a wavy line, its variation about the Earth's orbit is so small that the Moon's orbit is always concave to the Sun. If the Earth's orbit were drawn as a penciled circle 10 inches in diameter, the movement of the Moon would never take it outside the pencil mark. Fig. 126 shows this movement on a somewhat larger scale.

The Lunar Month. The lunar month, or the old calendar month, is 29.53 of our days in length. That is, the month from full Moon to full Moon, or from new Moon to new Moon, is 29.53 of our days. This is the month used by the Jewish calendar. It has been used by lunar calendars for perhaps six thousand years, and is called the *synodic* month. Some lunar calendars were referred to in an earlier chapter.

A figure of interest in astronomical work is the month with re-

spect to the stars, or the true period of revolution for the Moon. Because the Earth is moving about the Sun, it moves in the course of 29.53 days so that the full Moon is not in line with the same stars. The length of the Moon month by the stars, which is called the *sidereal* month, is 27 1/3 of our days.

The length of the *solar day* (day and night together) on the Moon is 29.53 of our days or exactly the synodic month. Any spot on the Moon has nearly fifteen of our days of continuous sunshine, and then nearly fifteen of our days of continuous darkness.

The Rotation of the Moon. Rotation, as stated in an earlier chapter, is a turning on an axis with respect to a relatively fixed system of lines. A wheel or a top rotates, and the Earth rotates also. Many wheels move as they rotate, and the Earth moves as it rotates. As the Moon goes around the Earth, it keeps the same side toward the Earth. A simple model to illustrate the motion will make it clear. Use a globe, perhaps with a map of the World on it, to represent the Earth, and use an apple or an orange to represent the Moon. Draw a long arrow on the floor under the globe. Push a long needle, preferably a knitting needle, through the apple or orange. Holding the needle horizontally, carry the apple or orange around the globe, being careful to keep the same side toward the globe. This represents the motion of the Moon around the Earth. As one does this, it is easy to see that the needle through the apple or orange turns around once with respect to the arrow on the floor while it is carried once about the globe representing the Earth. The Moon rotates once in a sidereal month.

You have read that the axis of the Earth is tipped so that in the northern Summer the Sun shines continuously on the north polar regions, and in the southern Summer the Sun shines continuously on the south polar regions. The axis of the Moon is tipped similarly, but only 6½°. As the Moon goes around the Earth, first the north pole and then the south pole is tipped toward the Earth. This makes it possible for more than half of the Moon to be seen, in spite of the fact that the same side is always turned toward the Earth. The eccentricity of the Moon's orbit makes it possible to see even a little more. The result is that 41 per cent of the Moon's surface is always visible. In addition, 18 per cent more can be seen part of the time. Fifty-nine per cent of the Moon's surface has been mapped, for that much is visible at least part of the time. Forty-one

per cent has never been seen. This effect, which makes it possible for us to see more than half of the surface of the Moon, is termed *libration.*

The Moon Seen Through the Telescope. As seen with the naked eye, the light and dark areas of the Moon form figures in which it is easy to imagine a man, a girl, a donkey, or a rabbit. With the telescope, these areas are resolved into detail. Even a small telescope shows ring mountains, mountain ranges, craters, mountain peaks, and smooth areas called seas. The mountains are seen best along the line dividing night and day on the Moon. This line is called the *terminator.*

Along the terminator, the contrast between the light and the dark portions together with the long shadows makes the mountains conspicuous. At the center of the Moon, near full Moon, the bottoms of the craters and the valleys are illuminated as well as the tops. There is no contrast and even a high mountain is very inconspicuous. For this reason, the best time to look at the Moon through a telescope is near first quarter, when the terminator is near the middle of the face of the Moon.

The Moon Has No Atmosphere. There is no atmosphere on the Moon. It has been known since the days of the Greeks that there must be very little. Here on the Earth, darkness does not come until nearly an hour after sunset. There is a period of twilight, caused by the atmosphere on the Earth bending and reflecting the Sun's rays. On the Moon darkness comes immediately. The edge of the shadow is very sharp between daylight and darkness. The most definite check for an atmosphere is the Moon's passage over a star, called an *occultation.* If there were an appreciable atmosphere, a star approaching the edge of the Moon would be dimmed slightly, and refraction would affect its position; but there is no such effect. The position is not affected at all, and the star retains its full brightness until its extremely sudden disappearance.

It can be calculated that the Moon is too small to hold an atmosphere. On the Earth, a body would have to travel seven miles per second to get away from the Earth, but no appreciable percentage of the molecules of our air go that fast, so that the gases of our atmosphere are held. Hydrogen has a velocity that is a bit too high, and as a result there is no appreciable hydrogen in our air, although there is much on the Sun.

The velocity of escape on the Moon, however, is only a mile and a half per second, just a little beyond the velocity of modern big

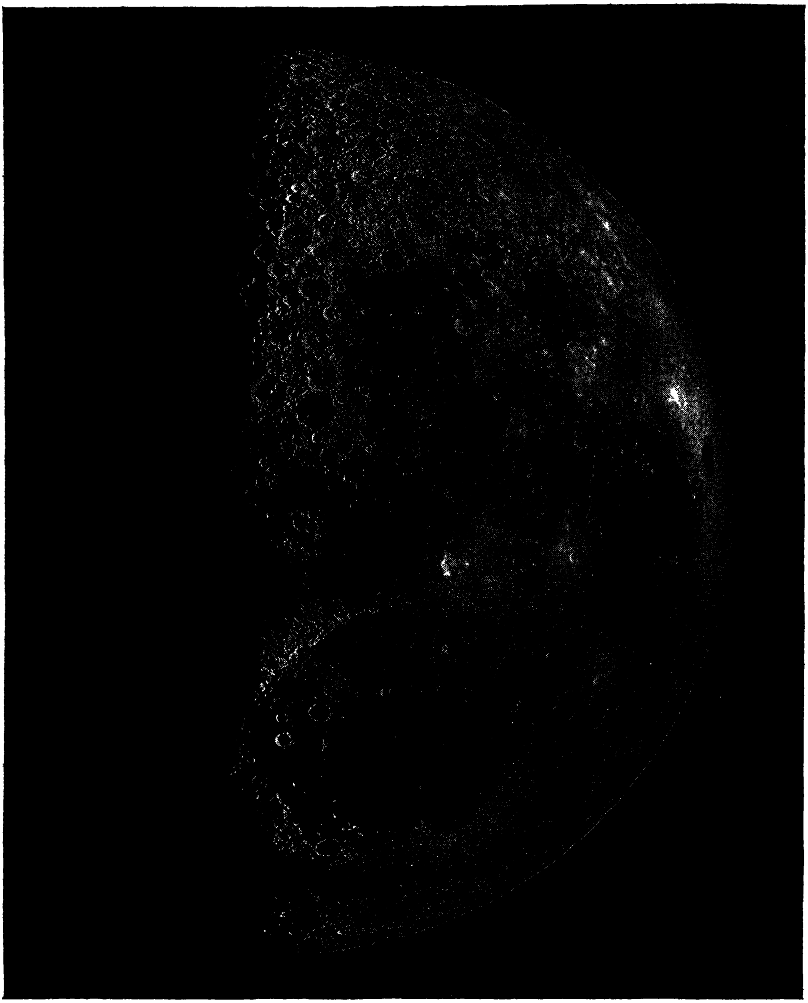


FIG. 127. The Moon near Last Quarter as Seen in an Inverting Telescope. Photograph from Mount Wilson Observatory

guns and rifles. The molecules of ordinary air attain a high enough speed to escape from the Moon, so if gases had been released on

the Moon, as they may have been by volcanic activities when the Moon was young, they would have escaped almost as fast as they were formed. It is assumed that the atmosphere of the Earth, and probably of the other planets, is stable now. The atmospheres pick up about as many molecules as they lose.

Temperature Changes on the Moon. There are enormous temperature changes on the Moon. The Moon has very light and porous rocks which heat up quickly. It has neither air nor water, and has an extremely long day. The temperature goes up to about 250° F during the day, and then very soon after sunset, goes down to about 150° F below zero.

No appreciable changes occur on the surface of the Moon. Photographs taken from year to year have shown no changes. There is neither air nor water to produce erosion, but enormous temperature changes might cause enough expansion and contraction to crumble the surface rocks to a certain extent. Without an atmosphere, meteors would strike directly and explode, with a force many times that of the explosion of an equal weight of nitroglycerin. The millions of tiny meteors striking each day would have pulverized a layer a few inches thick since the formation of the Moon. Studies indicate that the surface of the Moon is a fine dust, as would be expected, instead of bare rock.

Mountains on the Moon. The Moon is very mountainous. One can see with the telescope steep high mountains and big craters. The heights of the highest mountains exceed the heights of the highest mountains on the Earth. The highest mountains on the Moon rise about 26,000 feet above the surrounding plain. Mt. Everest on the Earth is 29,002 feet high, but that is its height from sea level. Measured from the surrounding plain, it is much less than 26,000 feet. The height of a lunar mountain can be calculated from the length of its shadow, and the known direction of the Sun at that time.

The largest *crater* on the Moon is Clavius which is about 140 to 150 miles in diameter. This is enormous as compared to craters on the Earth. The largest craters that have been found on the Earth are seven miles in diameter. There is one in Alaska about seven miles in diameter and another in Japan which is about the same size, but these are obviously nowhere near the size of those on the Moon.

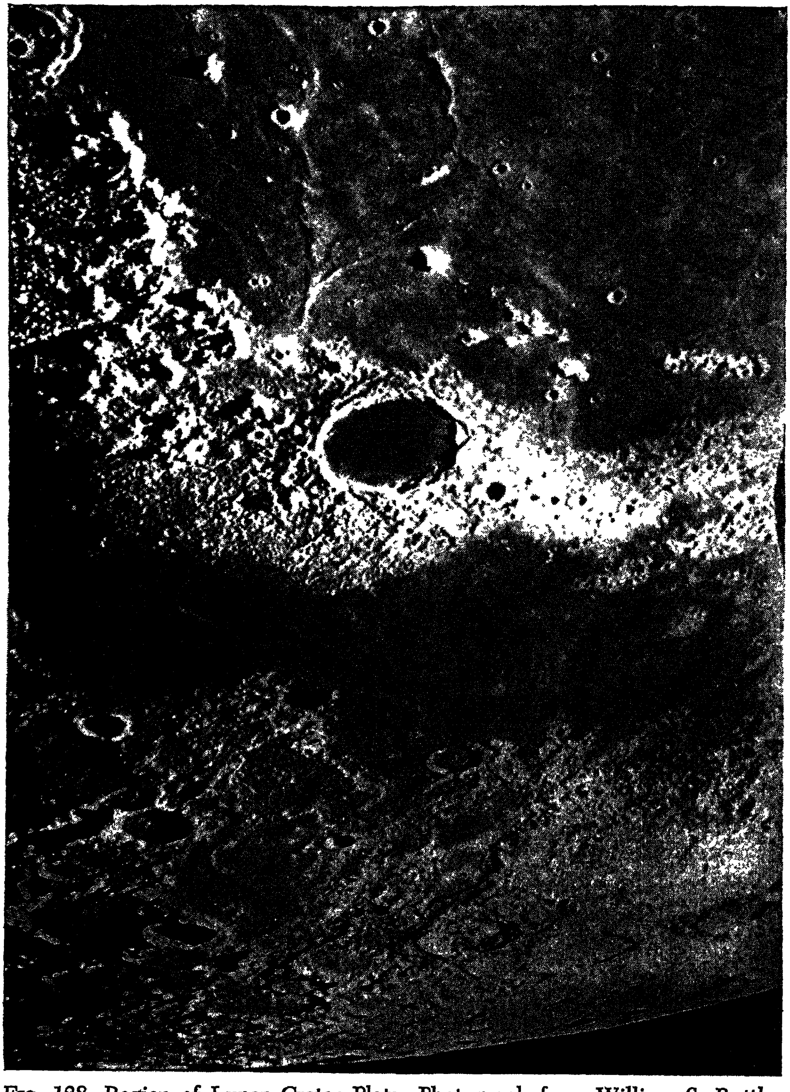


FIG. 128. Region of Lunar Crater Plato. Photograph from William S. Buttles

There are mountain ranges on the Moon, and there are *rays* and *rills*. The rays are long, light-colored streaks which radiate from some of the larger lunar craters. They extend to a distance of several hundred miles from the craters Tycho and Copernicus. The rays are only five or ten miles wide, and are neither elevated nor depressed appreciably with respect to the surrounding surface. The rills are deep, narrow, and sometimes crooked valleys. They appear to be deep cracks in the lunar surface, not associated with the craters.

The craters on the Moon are named after famous scientists, especially astronomers. Among the most conspicuous craters are Tycho, named after Tycho Brahe, the great Danish astronomer; Copernicus, named after the Polish astronomer to whom the Copernican Theory is due; Ptolemy, named after the great astronomer of classical times; Kepler, named after the astronomer who developed the laws of planetary motion; and Aristotle and Plato, named after well-known Greek scholars.

Some of the mountain ranges are named after mountain ranges on the Earth, as the Apennines and the Caucasus Mountains. The large relatively smooth and level areas, which were thought to be seas by Galileo and other early observers are called *maria* (singular, *mare*), the Latin word for seas.

There are *two theories on the formation of the lunar craters*: first, huge meteors striking and exploding; and second, volcanic activity.

Whatever the forces are that produce mountains, they would throw material higher and farther on the Moon, because the force of gravity there is only one-sixth what it is on the surface of the Earth. Given a volcanic explosion of equal intensity on the Moon and the Earth, the one on the Moon would throw material six times as far as the one on the Earth.

A meteor a few hundred feet in diameter would produce a tremendous explosion. It would be equivalent to setting off several times its own weight of nitroglycerin, and with the small force of gravity on the Moon would throw material to great distances.

As you have read, many of the craters on the Moon have rays radiating outward from them. A mathematical study indicates that the distribution of ray craters is random, which is what would be expected if they are of meteoric origin.

Another feature which has been studied is the depth of the floor

of the craters. Volcanic craters usually, although not always, have the floor above the level of the surrounding country. Meteoric craters, and those produced by the explosion of great mines in war-time, have the floor below the level of the surrounding country. Lunar craters on the whole have the floor below the level of the surrounding plain, which is in agreement with the meteoric theory.

Counts that have been made of lunar craters indicate they are somewhat more numerous in the mountainous regions, where vol-canoes are more numerous on the Earth. This suggests that at least some were produced by volcanic activity.

The fact that the surface of the Moon appears to be covered with a fine dust, presumably material pulverized by tiny meteors, should be kept in mind. With such an effect of small meteors apparent, one would expect an effect of large meteors, also.

From the rate of fall of meteors of all sizes observed on the Earth, a curve can be constructed and extended to give the rate of fall of the large, but rare, crater-producing meteors. Using this figure, and the lifetime of the Earth-Moon system as determined from the uranium-lead ratio of the oldest rocks, the number of meteorites which would strike an object the size of the Moon in its lifetime can be calculated. This number is of the same order as, but a little smaller than, the number of craters on the Moon. Since the Moon has practically no atmosphere, there would be practically no erosion, and a crater once formed on the Moon would last indefinitely, unless obliterated by a later eruption or by a later meteoric fall. The observed number of craters is what one would expect if many had been produced by the impact of great meteors and a considerable number by volcanic activity when the Moon was young.

From the preceding observations and calculations a definite conclusion cannot be reached, but it appears probable that both meteors and volcanic activity have contributed to the craters on the Moon.

A Hypothetical Visit to the Moon. If one could visit the Moon, he would notice a number of striking differences from conditions as we see them on the Earth. Everything would be lighter in weight, since gravity is only about one-sixth what it is on the Earth, but by the "no springs, honest weight scales," objects would weigh the same on the Moon as on the Earth, since the decrease would be in the same proportion, for the object as for the standard weights with

which it is being balanced. Inertia and momentum for a given mass would be the same on the Moon as on the Earth. An athlete throwing a baseball horizontally would throw at the same speed on the Moon as on the Earth. The jar of the baseball striking in the catcher's mitt would be the same, since traveling at the same velocity it would have the same momentum and the same kinetic energy.

The Earth would present an interesting spectacle in the lunar sky. The apparent diameter of the Earth as seen from the Moon would be four times the apparent diameter of the Moon as seen from the Earth. The Earth would remain in practically the same place in the lunar sky continuously because the Moon keeps the same face toward it. For the part of the Moon seen as the center of the face, the Earth would be continuously overhead, and for a point seen on the edge of the Moon, it would be seen on the horizon.

There is no air or water on the Moon. This means that rocks thrown out by an eruption or by an explosion would remain jagged. There would be no soil as we know it, but the rocks would be covered with a fine dust, the result of pulverization of the surface by meteors, and to a lesser extent by temperature changes.

Without air there would be no sound, and there would be no blue sky. By stepping into the shadow of a rock, one could have almost the blackness of midnight, and see fainter stars than it is possible to see on the Earth. There would be no twilight as the Sun goes down, but sudden darkness as soon as it disappears. Even the smallest meteors would strike the surface of the Moon at full speed, producing small and soundless, but violent, explosions. Each tiny meteor would pulverize many times its own weight of the lunar rocks. Without a protecting mantle of air in the long lunar day with continuous sunlight for nearly fifteen of our days, the surface of the Moon would become exceedingly hot. The temperature would rise above the boiling point of water, and the deadly ultra-violet rays, which are shut off by our atmosphere, would strike the Moon with full strength.

TIDES

As the Moon moves around the Earth in its orbit, the gravitational pull of the Earth on it is balanced by gravitational pull of the Moon on the Earth, but its pull for the near and far sides of the Earth is different from the pull for the center. As the solid Earth

is relatively rigid, this causes a piling up of the ocean waters on the side next to the Moon and on the side away from it. (See Fig. 129.) Two great waves are the result—one on the side where the ocean is pulled away from the solid Earth, and the other on the side where the solid Earth is pulled away from the ocean. The first wave is higher, but only a little higher, theoretically. This regular

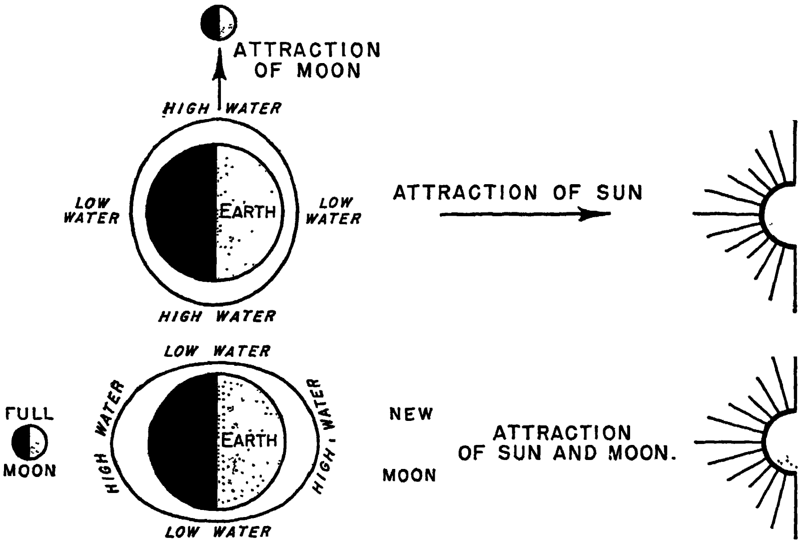


FIG. 129. Causes of Spring Tide (upper sketch) and Neap Tide (lower sketch)

rise and fall of the water is called the *tides*. The rotation of the Earth and the piling up of these waves against the continents complicate matters, so that high water, in general, is not directly beneath and opposite to the Moon.

The Sun contributes to the tides. Its attraction for the Earth is very much more than the attraction of the Moon for the Earth, but it is not the total attraction which causes the tide. It is the difference in attraction for the near and far sides of the Earth, and this difference is greater for the Moon. The Moon's tide-raising force is a little more than double that of the Sun.

The tides rise and fall twice per day, the average double interval being 24^h 51^m, precisely the interval between two successive pas-

sages of the Moon across the meridian. When the water level is highest, it is termed *high water*; when the water level is lowest, it is *low water.* (See Fig. 129.) When the tide is coming in, that is, when the water is rising, it is *flood tide*; when the tide is going out, that is, when the water is falling, it is *ebb tide.* High water comes at the end of flood tide, and low water comes at the end of ebb tide.

When the Moon is new or full, the tidal forces of the Sun and Moon are pulling together. The crest of the high water of the lunar tide falls on the crest of the high water of the solar tide, and the bottom of the low water of the lunar tide falls on the bottom of the low water of the solar tide. This results in considerably higher high water and lower low water than the average. These tides are called *spring tides.* In spite of the term spring tide, which suggests an annual occurrence, these great tides occur twice a month. At first quarter and last quarter the high water of the solar tides falls on the low water of the lunar tides. The Sun and Moon are not pulling together, but opposite one another. This results in considerably smaller tides than the average, which are known as *neap tides.* The neap tides have lower high water and higher low water than the average. Spring and neap tides are illustrated in Fig. 129.

The very highest tides occur where the tidal wave is piled up as it rolls into a bay. A V-shaped bay on the eastern coast of the continent is best, since the V-shape piles up the water, and the tidal wave rolls across the oceans from east to west. There are tides on the western coasts of continents, but not the highest tides. The Bay of Fundy, between Maine and Nova Scotia, is V-shaped and on the eastern coast of a continent. As a result it has exceedingly high tides, the difference between high and low tides being about forty feet.

Prediction of Tides. The prediction of the times of high and low water is a matter of considerable importance, especially in navigation. Many harbors can be entered by large vessels only at the time of high water. In other harbors, the problem is met by tidal basins which are filled at high water, and then as low water approaches, the gates are opened allowing this stored water to flow into the harbor and preventing the water level from dropping too low.

The prediction of the tides is very complicated, and it is different for each port. The actual calculation for American navigators

is done by a machine in Washington, D.C. The figures that remain constant for a port are set up, and then as the figures for the Moon and Sun are put in, the machine prints rapidly the times of the tides for that port.

Friction of the Tides. In an earlier chapter you read that the friction of the tides has been calculated. Although the tides are doing work at the rate of nearly two billion horsepower, the retarding of the Earth's rotation would lengthen the day by a second only after about 150,000 years.

Exercises

1. What causes the phases of the Moon? Be able to identify in the sky any phase of the Moon.
2. Do the horns of the Moon point away from or toward the Sun? Why? Can we see stars inside the cusps of the crescent new Moon?
3. What is the apparent magnitude of the full Moon? How much brighter is the full Moon than the quarter Moon?
4. What is the apparent path of the Moon in the sky?
5. What are some bright or important full Moons? Explain each.
6. What is the shape of the Moon's orbit with respect to the Earth? With respect to the Sun?
7. What terms with regard to the Moon's orbit are analogous to aphelion and perihelion?
8. What would be the gravitational pull at the surface of the Moon if the Moon's radius were ¼ and its mass 1/100 the Earth's?
9. What are the two measures of the month by the Moon, and how do they differ?
10. What is meant by the term "libration"?
11. What are the physical conditions on the Moon? What is the height of the highest mountains and the width of the largest craters? How do they compare with the Earth's topography?
12. What causes the Earth's tides? What is the average period from one high tide to the next and the reason for its length?
13. Define spring tide and neap tide.
14. What commercial importance and scientific interest do tides have?

☆ XIV ☆

Eclipses

Eclipse means "cut off light." When the Moon passes between the Earth and the Sun, the Moon's shadow falls on the Earth, and, for persons in the shadow, the Moon is seen projected on the face of the Sun, cutting off its light. This is an eclipse of the Sun. When the Moon passes into the shadow of the Earth, the Earth is cutting off the sunlight, making an eclipse of the Moon.

As the Earth and Moon are dark bodies illuminated by the Sun both have shadows, and as the Sun is much larger, the shadows are cone-shaped. The length of the Earth's shadow is 860,000 miles, or nearly three times the distance of the Moon from the Earth. The length of the Moon's shadow, on the average, is 232,000 miles, or not quite the average distance of the Moon from the Earth. If the shadow of the Moon, when it reaches beyond the Earth, passes across the Earth's surface, persons inside the shadow see the Sun completely covered by the Moon. This is a *total eclipse* of the Sun. If the shadow does not reach as far as the Earth, and the Moon passes directly between the Sun and the Earth, persons who see the Moon pass over the Sun will not see it completely covered. When the Moon is directly over the Sun, a ring of light will show about the Moon. This is called a ring-form, or *annular eclipse.*

The apparent diameter of both the Sun and of the Moon is just about half a degree. If, at the time of a solar eclipse, the apparent diameter of the Moon is a little greater than that of the Sun, a total eclipse occurs. If the apparent diameter of the Moon is a little less than that of the Sun, an annular eclipse occurs.

The shadow of the Earth or the Moon is called the *umbra.* Persons inside the area covered by the umbra at the time of an eclipse of the Sun will see a total eclipse. Surrounding the umbra

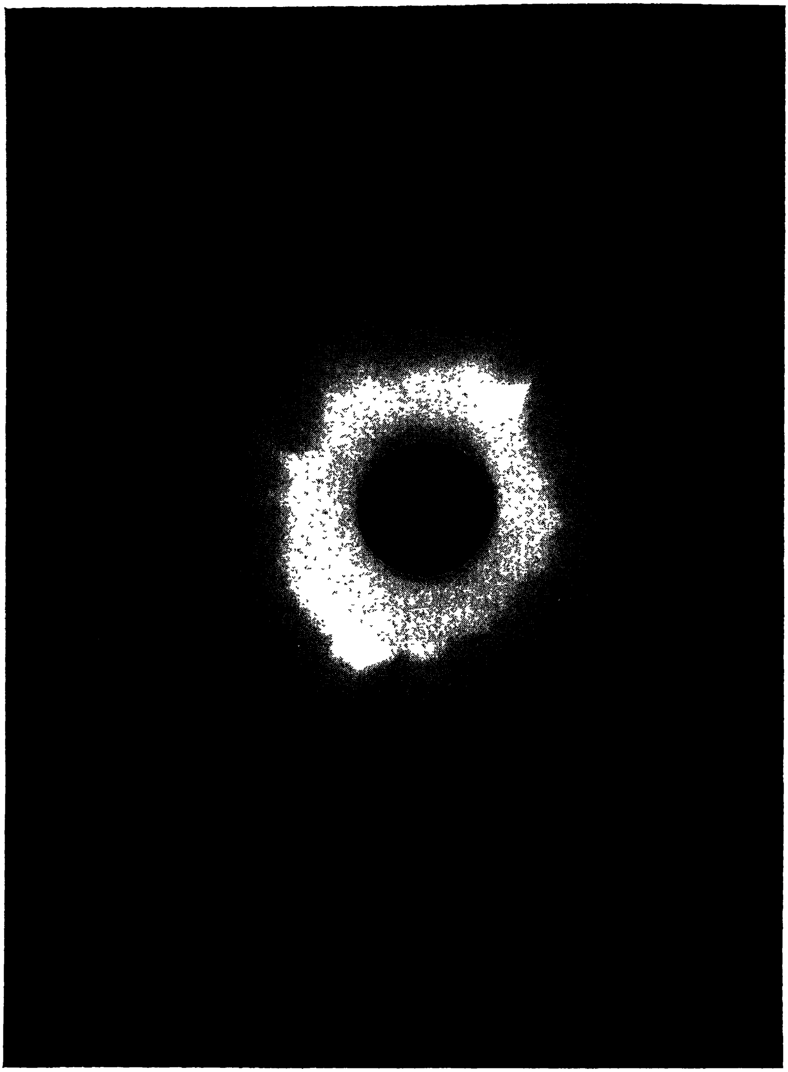


Fig. 130. Total Solar Eclipse of June 8, 1937. Photograph from Dr. Paul A. McNally, S.J.

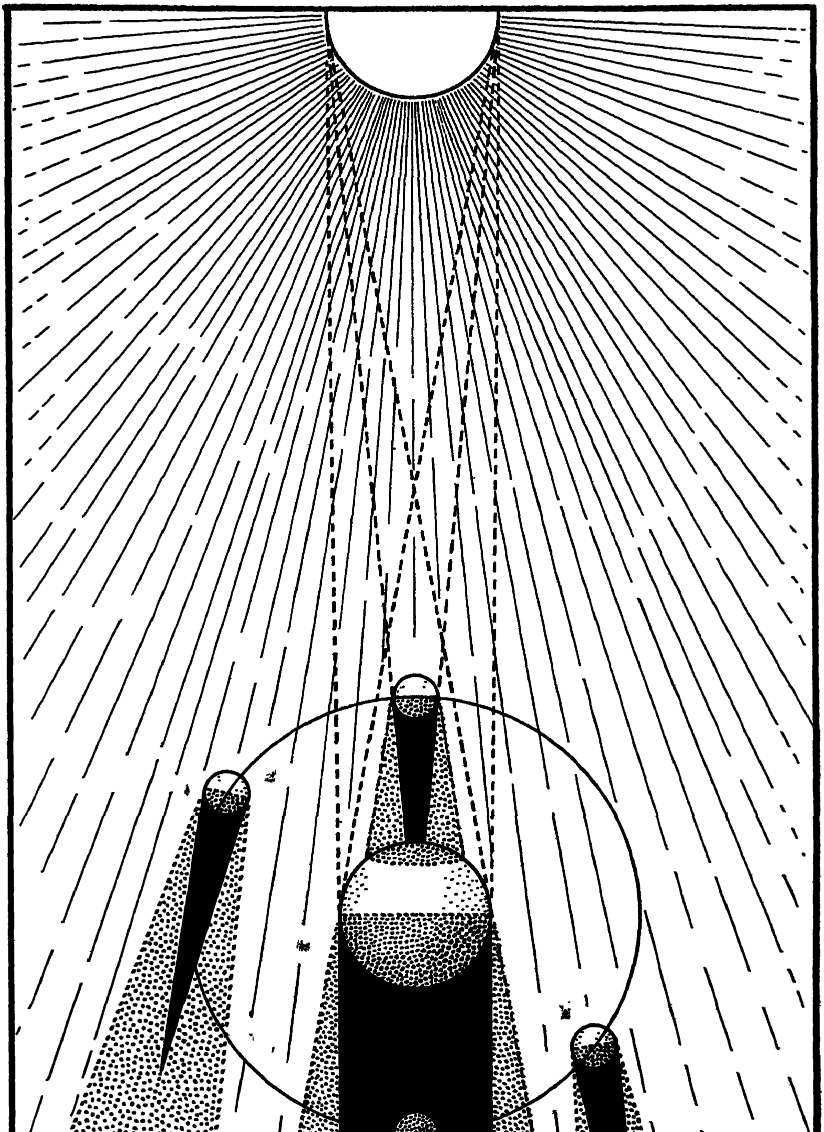


FIG. 131. Umbra and Penumbra of the Shadows of the Earth and Moon

is a region within which persons will see the Sun partially, but not completely, covered by the Moon. This is the *penumbra.* Persons inside the penumbra see a *partial eclipse.* (See Fig. 131.)

For eclipses of the Moon, the term eclipse is used only if the Moon enters the umbra, or the real shadow, of the Earth. It is a total eclipse if the Moon passes completely into the umbra, and it is a partial eclipse if, as the Moon passes the shadow, part but not all of the Moon enters the umbra. The mean length of the Earth's shadow is 857,000 miles, and at the distance of the Moon it is two or three times the diameter of the Moon. There can thus be no "annular" eclipse of the Moon.

Eclipses of either the Sun or the Moon can occur only if the Earth, Sun, and Moon are nearly in a straight line. Since the Moon's path in the sky is tipped 5° with respect to the ecliptic, the Earth, Sun, and Moon can be in a straight line only when they are on the line of intersection of the plane of the ecliptic and the plane of the Moon's orbit. Since the Earth, as it moves about the Sun, crosses this line twice per year, at least two eclipses can be expected to occur each year. As the Moon moves around the Earth, it usually passes above or below the shadow at full Moon, so at most full Moons during the year there is no eclipse of the Moon. For the same reason, at new Moon, the Moon's shadow usually passes above or below the Earth, and at most new Moons during the year there is no eclipse of the Sun. Eclipses can occur, as we said, only when the Earth is quite close to the line joining the intersections of the ecliptic and the Moon's orbit. Hence, each year the eclipses of a given kind occur about six months apart.

When the Earth is nearly in line, there will be an eclipse if the Moon gets in line. The Moon can be in line at either new Moon or full Moon, so that eclipses often occur in pairs, an eclipse of the Sun at new Moon followed by an eclipse of the Moon at the next full Moon, or vice versa.

Relative Number of Eclipses of the Sun and Moon. To understand the relative number of solar and lunar eclipses look at Fig. 132. In this figure a line is drawn from the "top" of the Sun past the "top" of the Earth, and another line is drawn from the "bottom" of the Sun past the "bottom" of the Earth. These lines mark a cone inside of which the Moon cannot go without causing an eclipse. The cone is larger on the side of the Earth next to the Sun than it

is on the side of the Earth away from the Sun. When the Moon cuts into the cone on the larger side, we have an eclipse of the Sun, and when it cuts in on the smaller side, we have an eclipse of the Moon. Obviously, there should be more eclipses of the Sun than of the Moon. Actually there are about four eclipses of the Sun to three of the Moon.

The maximum number of eclipses in a year is seven, which may be five of the Sun and two of the Moon, or four of the Sun and three of the Moon. The minimum number of eclipses in a year is two, both of the Sun. These figures are for the whole World; for one place the relative number is quite different.

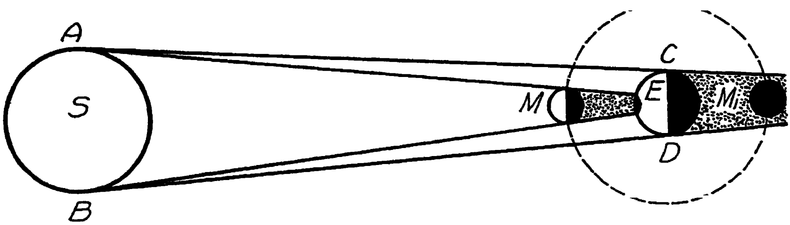


FIG. 132. The Limits for Eclipses of the Sun and Moon

By reference to the same figure it can be seen that an eclipse of the Moon can be observed from half the Earth, while an eclipse of the Sun can be observed as total only from the narrow path marked out by its shadow. Assuming the path is 100 miles wide, which is not far from the average, it would take 250 total eclipses to cover the Earth. Since there are about seventy total eclipses of the Sun per century, this means that it would take 360 years to cover the Earth with total eclipses of the Sun. Actual calculations of eclipses visible from certain cities in the United States and Europe indicate that for these latitudes total eclipses recur after an interval even greater than 360 years. Eclipses of the Moon, although they occur less frequently, are visible much more often at a given place. Since half of the Earth can see the Moon in eclipse, about half the eclipses of the Moon are visible from any one place.

Occultations. As the Moon moves around the Earth, it must pass between the Earth and many stars each month. When it passes in front of a star, it eclipses it. This special type of eclipse is known

as an *occultation* of the star. As you read earlier the disappearance of a star when it is occulted is one of the most instantaneous things in nature. The timing of an occultation fixes the position of the Moon accurately. The *American Ephemeris and Nautical Almanac*

FIG. 133. A Map of Eclipse Paths from Oppolzer's *Canon der Finsternisse*

gives predictions each month for the occultations of the brighter stars and certain astronomers observe these occultations regularly.

Prediction of Eclipses. The prediction of eclipses involves accurate positions for Sun, Earth, and Moon, and the rotation of the Earth as well. This means that it involves considerable mathematical work. Unless extreme accuracy is desired, however, the predictions can be made using the tables and maps in Oppolzer's *Canon Der*

Finsternisse, published in Vienna in 1887. This book gives data for all eclipses of both Sun and Moon from 1207 B.C. to 2161 A.D. inclusive. The approximate paths for the total eclipses of the Sun are drawn on maps, and more accurate paths and the times of beginning and ending for any locality can be calculated from quantities which he has tabulated for each eclipse. (See Fig. 133.) All eclipses are calculated with the greatest accuracy by the U. S. Naval Observatory. Their predictions, including maps and tables, appear each year in the *American Ephemeris and Nautical Almanac,* but they are available only one or two years in advance.

The Saros. The saros is a period of 18 years, 11 1/3 (or 10 1/3) days for the recurrence of solar eclipses. This period was known to Chaldean astronomers centuries before the time of Julius Caesar, and it was used by them for the prediction of eclipses. The eclipses of May 28, 1900, and of June 8, 1918, are instances of the return after that interval of practically the same eclipse. At successive returns an eclipse is moved about eight hours (one-third day) west in longitude, and a little north (or south) in latitude.

Solar Eclipses

The farther the Moon is from the Earth, the smaller the diameter of the shadow where it strikes the Earth, and the shorter the eclipse tends to be. The farther the Earth and Moon are from the Sun, the longer the shadow cone, and the longer the eclipse tends to be. The nearer the Sun is to overhead in mid-eclipse, the longer the eclipse tends to be. This makes eclipses in the tropics longer than those in the temperate zones.

Duration of Total Solar Eclipse. The theoretical maximum duration of totality for an eclipse of the Sun has been calculated as $7^m\ 58^s$, but it exceeds seven minutes for only a few eclipses. The total eclipse of June 8, 1937, had a longer maximum duration than any in the preceding twelve centuries, $7^m\ 4^s$. This duration will be exceeded by two other eclipses coming within the next few hundred years. The eclipse of June 20, 1955, will have a maximum duration of $7^m\ 6^s$, and the eclipse of June 25, 2150, will have a maximum duration of $7^m\ 14^s$.

Total Solar Eclipses Visible in the United States. Between the eclipse of 1932 and the year 2017, the paths of seven total eclipses

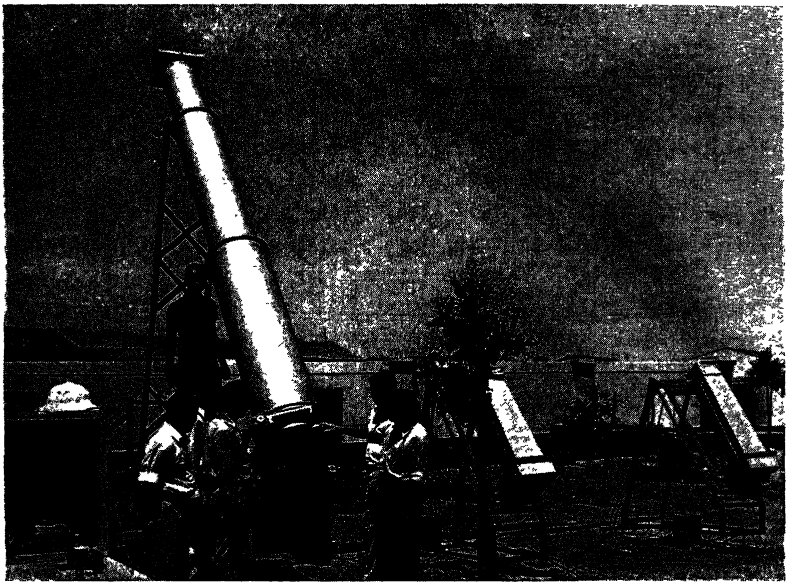


FIG. 134. Astrographic Camera for Recording Solar Eclipse. Photograph from Dr. Paul A. McNally, S.J.

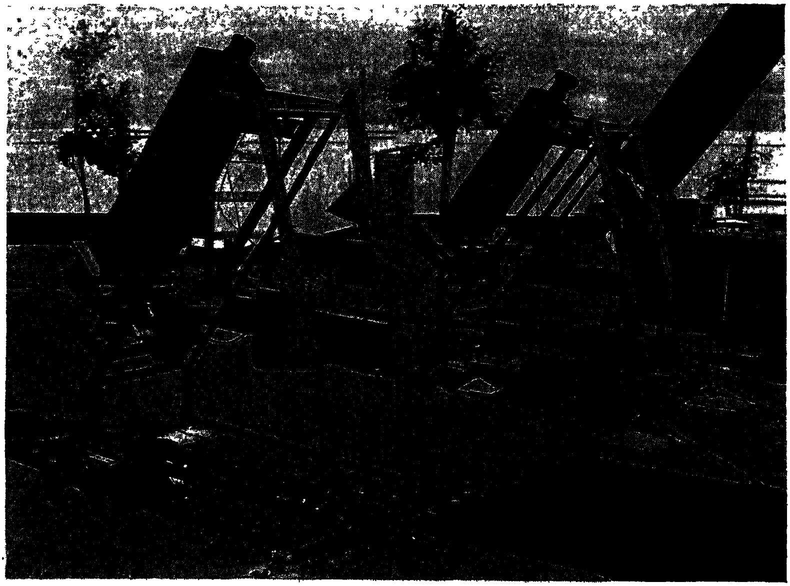


FIG. 135. Astrographic Cameras for Photographing a Total Solar Eclipse, Patos, Brazil, October 1, 1940. Photograph from Dr. Paul A. McNally, S.J.

will cross parts of the United States. For the first three, Americans will see the eclipse (with clear weather) just after sunrise, so the view will not be good. For the last four, the chances are better. These eclipses are as follows:

July 9, 1945, visible in Idaho and Montana just after sunrise.
June 30, 1954, visible just after sunrise in Minnesota and Wisconsin.
October 2, 1959, visible just after sunrise in Massachusetts.
July 20, 1963, visible in Maine in the afternoon; the next opportunity to get a good view of a total eclipse of the Sun in the United States.
March 7, 1970, visible in Florida, Georgia, and the Carolinas, another good view if weather is clear.
February 26, 1979, visible in Idaho and Montana in the middle of the forenoon.
August 21, 2017, visible all the way across the United States, like the one of June 8, 1918.

Eclipse Expeditions. Since total eclipses of the Sun are rare at any one place, an astronomer who is interested in eclipse problems practically never finds an astronomical observatory in the path of the eclipse. If the eclipse is to be observed, it must be observed with equipment transported to the proper site. The approximate site for the observations is selected usually at least a year before the eclipse. To allow time for testing and adjusting, the equipment is selected, or built, and put in good working order several months before it must be packed for shipment.

Some, at least, of the observers plan to arrive at the site several weeks before the eclipse. The equipment must be set up, and provisions made for housing equipment and observers. The longitude and latitude of the site must be determined, and "dress rehearsals" held before the day of the eclipse. At rehearsal, each observer does exactly what he is planning to do at the time of the eclipse.

The site for observing the eclipse is selected only after a study of probable weather conditions for that locality and season. Usually, therefore, the weather is clear, but occasionally clouds prevent any observations, and there is no return other than experience for the time and money expended.

Phenomena of a Total Solar Eclipse. As the Moon moves over the

Sun, if the weather is clear, the decrease in light will not be noticeable until more than half of the Sun is covered. It will be interesting, however, to watch the progress of the eclipse using some old film, or in some other way as suggested later. The decrease in light as totality approaches is very rapid. It will be recalled that the

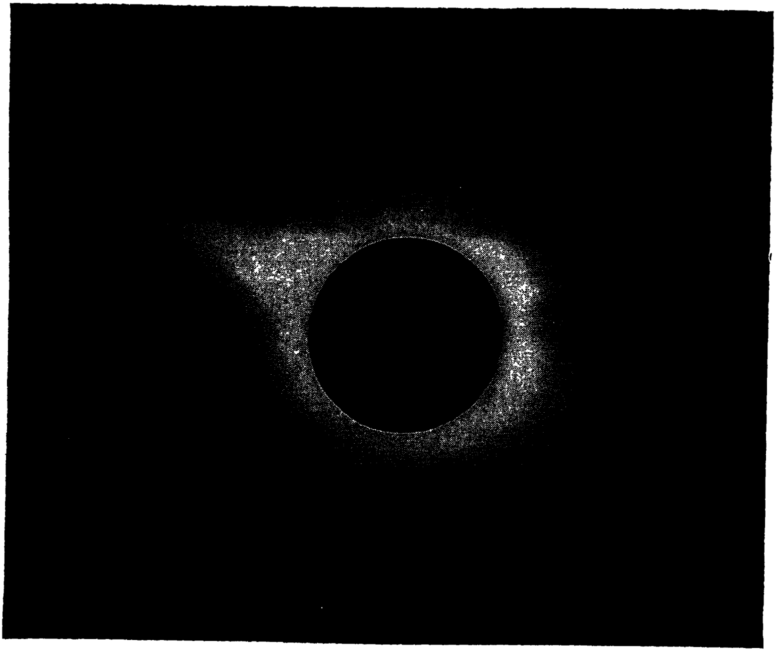


FIG. 136. Total Solar Eclipse of August 31, 1932. Photographed by Rev. Paul A. McNally, S.J.

brightness of full sunlight is equivalent to some 385,000 full Moons. When only one-thousandth of the Sun remains uncovered, the light is still equivalent to nearly 400 full Moons. Such a small sliver of the Sun is covered quickly, however, dropping the light from a few hundred full Moons to little more than the light of the full Moon in about a minute. There are many stories of animals thinking night is approaching, and birds and chickens going to roost. Just before the Moon covers the Sun completely, the so-called shadow bands appear.

As the last sliver of Sun disappears behind the Moon, it often is

broken up by the irregularities of the mountains of the Moon's edge into a number of points of light. These points of light look like beads and are called *Baily's beads.* As the beads disappear, the rosy prominences and the pearly gray corona appear. They give about half the light of the full Moon, but in an average eclipse the general light during totality is more than the light of the full Moon. The path of the shadow is narrow and considerable light is reflected into the region of totality from clouds and dust outside. The darkness is

FIG. 137. Solar Eclipse Spectrographs of National Geographic Society set up at Patos, Brazil, October 1, 1940. Photograph from Rev. Paul A. McNally, S.J.

enough, however, for the brighter stars and planets to be seen shining in the sky.

Just as totality ends, the reappearing edge of the Sun is broken up by the lunar mountains so that "Baily's beads" are seen again. The bright edge, reappearing after the eyes have adjusted themselves to a light little greater than moonlight, dazzles the eye and fogs the photographic plate. Moving pictures of an eclipse show at this phase what is called the "diamond ring." The corona shows as a complete ring, and a small but brilliant edge of the Sun makes

a spot of light resembling the set of a ring, at one place. The effect has been seen visually, although not often.

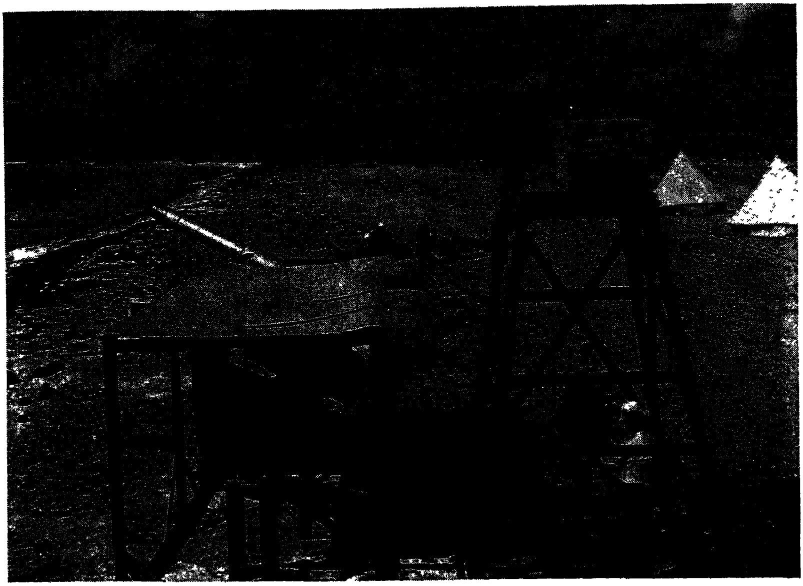


FIG. 138. Instrument for Measuring Polarization of Coronal Light at Total Solar Eclipse of June 8, 1937. National Geographic Society, U. S. Navy Expedition to Canton Island. Photograph from Rev. Paul A. McNally, S.J.

Scientific Observations. The following are the more important observations made by scientific expeditions to observe total eclipses of the Sun:

1. Accurate times for beginning and ending of totality; used for correcting tables of the Moon's motions.
2. Spectroscopic observations of "flash" spectrum; for a study of the elements in the Sun's atmosphere.
3. Spectroscopic studies of the corona; for composition, and for velocity of motion.
4. Photographs of the corona, with various exposures for inner and outer portions.
5. Photoelectric measurements of the light of the corona.
6. Measures of polarization of light of corona.

7. Photographs of stars surrounding the eclipsed Sun. These can be studied for:
   a. Possible intra-Mercurial planets. It is known now that these can be no bigger than a small planetoid if they exist.
   b. The gravitational deflection predicted by the relativity theory.

Watching a Partial Eclipse. As you have read previously, total solar eclipses are rare sights. Few people see one without traveling hundreds of miles to get into the path of the shadow; but everyone can see partial eclipses without traveling, since any eclipse of the Sun can be seen as partial over a considerable portion of the Earth.

Because of the great brilliance of the Sun, one should not look at it directly, or the eye may be seriously injured. The simplest protection for the eyes is fogged film, or the use of several old photographic negatives. One should be sure he is using enough to protect the eye, so that the portion of the Sun remaining is seen as a dull red rather than as a dazzling brightness.

Still another method of watching an eclipse, especially where one desires to show it to a whole group, is to project an image by letting sunlight shine through a small hole in a piece of paper. If a large piece of paper is placed in a window, and a small opening is made to admit the sunlight into a relatively dark room, a larger image of the partially eclipsed Sun can be made. As the Moon covers the face of the Sun, the portion not covered becomes a crescent, and all the spots of light become crescents. This is true for the spots under trees, for the spots made by the sunlight shining through small holes in window shades, and for images of the Sun projected in any other way.

Lunar Eclipses

An eclipse of the Moon is caused by the Moon cutting across the shadow of the Earth. The closer the Moon is to the Earth, the greater the diameter of the shadow where it must cut through, and hence the longer the eclipse. The farther the Earth is from the Sun, the greater the diameter of the shadow at a given distance from the Earth. In other words, for maximum duration, Sun, Earth, and Moon should be in just about a straight line at the middle of eclipse.

Maximum Duration of Totality. The three important conditions for maximum length are attained, for practical purposes, for two or three eclipses each century. The last such occasion was on the night of July 22-23, 1888. That eclipse was total for $1^h\ 42^m.4$, the longest possible total eclipse of the Moon. The eclipse of 1953 will be total about as long as the one of 1888, but it will not be completely visible in any part of the United States.

Visibility of Totally Eclipsed Moon. The eclipsed Moon is illuminated by light refracted into the shadow by the Earth's atmosphere. Although distinctly visible with a clear sky, only a little haze makes it invisible. Several reports of the eclipsed Moon becoming invisible must be due to local haze, for observers at other places could see the eclipse in question. However, an English astronomer reported that during the total lunar eclipse of June 10, 1816, the eclipsed Moon became invisible, and no other observer has contradicted him. The atmosphere of the Earth, especially around the "rim" of the Earth as seen from the Moon, must have been very dusty or cloudy to prevent the usual illumination of the eclipsed Moon. Perhaps this was due to the great volcanic eruption of Tamboro, on Sumbawa in the East Indies, from April 7 to April 12, 1815, from which the dust circled the Earth in the upper atmosphere.

Scientific Observations. The following are some of the observations made by astronomers during a total eclipse of the Moon:

1. Measurements of the heat radiated during a lunar eclipse show a very rapid drop in temperature of the surface rock. This checks other indications that the surface rocks, in general, are light and porous.
2. As you have read previously, solar eclipses furnish checks on the Moon's position and on a probable change in the length of our day. Occultations furnish another, and, when the Moon is in eclipse, relatively faint stars can be seen right at the edge of the Moon. Astronomers observe occultations of these stars, and obtain more accurate positions than are possible when the Moon is not in eclipse.
3. Some astronomers have wondered whether the Moon might have a small satellite revolving about it as the Moon revolves about the Earth. From a study of photographs made at the time of a lunar eclipse it appears that the Moon can have no satellite with a diameter exceeding half a mile.

4. At the time of a lunar eclipse the Moon is illuminated faintly by light bent into the Earth's shadow by our atmosphere. If the air along the "rim" of the Earth, as seen from the Moon, is cloudy or dusty, little light will be bent into the shadow, except that coming through the stratosphere, or upper one-fourth. If the lower air is exceptionally clear, a considerable amount of light will be bent into the shadow by the lower three-fourths of our atmosphere.

From a study of the illumination of the Moon during total eclipses, Dr. W. J. Fisher of Harvard announced about 1925, that the air over the Antarctic regions was the clearest on the globe, and that the air over the tropics was clearer than that over the north temperate and north polar regions. The Byrd expeditions have confirmed his result for the Antarctic.

In the table below are listed the total lunar eclipses which will be visible in the central states from 1943-1970 inclusive. The list is compiled from data in Oppolzer's *Canon der Finsternisse*. The times given are Central Standard.

TABLE XII. LUNAR ECLIPSES VISIBLE FROM 1943-1970

Year	*Date*	*Mid-totality* hr.	min.	*Duration* hr.	min.
1945	Dec. 18	8	22 p.m.	1	23
1949	Apr. 12	10	12 p.m.	1	28
1949	Oct. 6	8	54 p.m.	1	10
1950	Sept. 25	10	15 p.m.	0	43
1953	Jan. 28	5	50 p.m.	1	20
		(Moon rises in total eclipse)			
1954	Jan. 18	8	34 p.m.	0	38
1956	Nov. 17–18	12	47 a.m.	1	15
1960	Feb. 13	2	30 a.m.	1	35
1960	Sept. 5	5	23 a.m.	1	25
		(Moon sets in total eclipse)			
1961	Aug. 25	9	08 p.m.	0	14
1963	Dec. 30	5	07 a.m.	1	22
1964	June 24	7	07 p.m.	1	35
		(Moon rises after mid-totality)			
1964	Dec. 18	9	35 p.m.	1	02
1967	Oct. 18	4	16 a.m.	0	55
1968	Apr. 12	10	49 p.m.	0	55
1968	Oct. 6	5	41 a.m.	1	00
		(Moon sets near mid-totality)			

Exercises

1. Calculate the length of the Earth's shadow cone if the diameter of the Earth is 8000 miles, the diameter of the Sun 864,000 miles, and the Sun's distance from the Earth 93,000,000 miles.
2. Define umbra and penumbra.
3. How do total, annular, and partial eclipses of the Sun differ?
4. Using the data from problem 1, calculate the diameter of the cone of the Earth's shadow at the distance of the Moon, 240,000 miles from the Earth. How many times the Moon's diameter is this figure?
5. Are the phases of the Moon and eclipses of either the Sun or Moon the result of the same cause? Explain.
6. What is the relative number of lunar and solar eclipses?
7. What is an occultation?
8. How can modern astronomers predict eclipses?
9. What is the Saros, and when was it discovered?
10. Why are eclipses in the tropics longer than those in the higher latitudes?
11. What are Baily's Beads?
12. Give the important scientific observations made at the time of a total eclipse of the Sun.
13. What is the maximum duration of totality for an eclipse of the Sun? for an eclipse of the Moon?
14. What are some of the useful scientific observations made at the time of a total eclipse of the Moon?
15. How could Dr. Fisher study the air over the Antarctic region without leaving the United States?

☆ XV ☆

The Paths of the Planets

The *solar system* includes the Sun, and the bodies that revolve around it. The word solar comes from Sol, the Latin name for the Sun. The bodies that revolve around the Sun include nine principal planets, of which the Earth is one; thousands of minor planets, called planetoids or asteroids; twenty-eight known satellites, of which our Moon is one, that revolve around the principal planets; hundreds of comets; and countless meteors.

Early people noticed that the stars in the night sky maintained fixed positions with respect to one another, with a few exceptions. These star-like objects which moved about over the sky pictures were named *planets*, or wanderers, from the Greek word "planetes," meaning wandering. Early people knew five planets, but they thought they saw seven since Mercury and Venus were each given separate names in the morning and evening sky. Early Greek and Roman names of the "seven" planets were Apollo (Mercury in the morning sky), Mercury (Mercury in the evening sky), Phosphorus (Venus in the morning sky), Hesperus (Venus in the evening sky, Mars, Jupiter, and Saturn. Later Greek astronomers found that Mercury in the morning sky and in the evening sky were the same planet, and that Venus in the morning sky and in the evening sky were the same planet. This left only five planets, but as the number seven had become sacred, especially to the astrologers, the Sun and the Moon were added by some to preserve this number.

In 1543, the revolutionary book of Copernicus appeared. The Earth became one of the planets, and the Sun and Moon could not be included by anyone. For more than 200 years afterward there were six known planets. These were Mercury, Venus, Earth, Mars, Jupiter, and Saturn. In 1781, Sir William Herschel discovered

Uranus, and since that time Neptune and Pluto have been discovered making now nine known principal planets. Beginning with the innermost, or closest to the Sun, they are as follows: Mercury, Venus, Earth, Mars, Jupiter, Saturn, Uranus, Neptune, and Pluto.

Although the planets look like stars, in reality they are very different. The stars are big hot bodies, like our Sun. The planets are smaller cold bodies, like our Earth. The stars are gaseous throughout, while the planets are solid bodies. The stars are selfluminous, shining by their own light, while the planets are dark nonluminous bodies, shining only by reflecting the light of the Sun.

Bode's Law. There is a curious relation between the distances of the planets from the Sun, which was brought to the attention of astronomers by J. E. Bode in 1772. The relation appears to have been noticed by a man named Titius some years earlier. Bode's Law may be illustrated as follows:

Write a series of 4's. To the second 4, add 3; to the third 4, add 2×3 or 6; and so on, doubling the added number each time as follows:

Planet =	M.	V.	E.	M.		J.	S.	U.	N.	P.
	4	4	4	4	4	4	4	4		4
	0	3	6	12	24	48	96	192		384
Sum ÷ 10 =	.4	.7	1.0	1.6	2.8	5.2	10.0	19.6		38.8
Distance =	.39	.72	1.00	1.52	2.77	5.20	9.54	19.2	30.1	39.5

It will be noticed the sum divided by ten, for each planet, is approximately equal to the distance of the planet from the Sun. The "distance" is obtained by dividing the distance of each planet from the Sun, expressed in miles or kilometers, by the Earth's distance from the Sun expressed in the same unit. Each distance is expressed in terms of the Earth's distance.

It will be noticed too, that the agreement is good, excepting that Bode's law places a planet between Mars and Jupiter, and it fails to represent Neptune. When Bode called the attention of the astronomers to this law, Saturn was the outermost planet known. The agreement was so close that, although no physical basis was known for this law, astronomers suspected that a planet existed between Mars and Jupiter. When Herschel discovered Uranus in 1781, at a distance very close to that represented by Bode's law, the interest in a possible planet between Mars and Jupiter became more wide-

spread. A group of twenty-four planet hunters, mainly German, was organized to search for this supposed planet.

On January 1, 1801, Piazzi (1746-1826), found a seventh magnitude moving object, which he named Ceres. It was observed for six weeks and then was lost in the evening twilight. Piazzi was not a member of the group of planet hunters and with the methods of communication of that time, the planet hunters did not learn of the discovery until the object was lost. During the Summer and Autumn of 1801, Gauss (1777-1855), a brilliant young German astronomer, developed a new method of orbit calculation by which a reasonably good orbit could be calculated from a short series of observations. He applied the new method to the lost Ceres, calculated its orbit from the observations of Piazzi, and it was rediscovered at once.

Ceres proved to be at just about the distance predicted by Bode's law. In fact, the distance 2.77 in the preceding table is that of Ceres. Astronomers were somewhat surprised, therefore, when another little planet, later named Pallas, was discovered in 1802 while search was being made for Ceres. Another was found in 1804, and still another in 1807. Thousands of these minor planets, called asteroids or planetoids, are now known.

The Apparent Motions. As seen from the Earth, the planets Mercury and Venus seem to move back and forth past the Sun, from a certain distance east of the Sun to about the same distance west of it, and back again. Mercury is never more than 28° from the Sun, and Venus is never more than 47° from the Sun, so neither can be seen in the middle of the night.

The other planets move eastward among the stars in a general way (the right ascension increases), but near the time when the planet is rising in the east at sunset, it reverses its motion and moves westward for a time. These planets move in loops, one loop each year, the eastward motion being termed direct, and the westward motion retrograde.

The following terms are used often in referring to the positions of planets as seen from the Earth.

Elongation of a planet refers to the apparent angle between that planet and the Sun. It is used especially for the inner planets, Mercury and Venus. Greatest elongation is the greatest apparent

angle between the Sun and the planet. For Mercury, greatest elongation varies from 18° to 28°, and for Venus, greatest elongations is 47° to 48°. In Fig. 139 the elongations of Venus are *V* and *V′*.

Conjunction refers to the time when a planet is passing another heavenly body. When Venus is passing from the morning to the

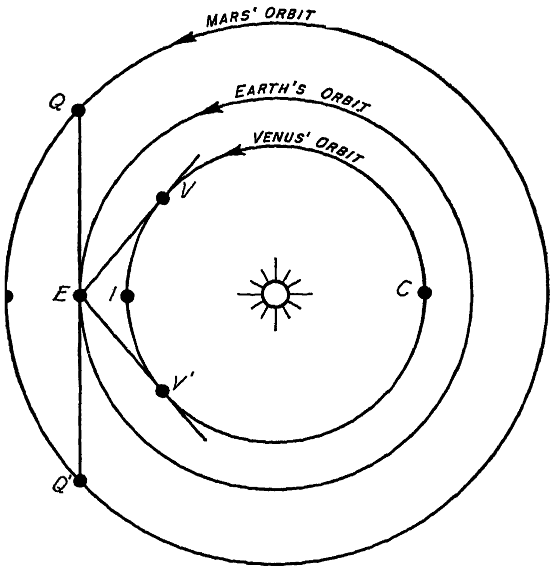


FIG. 139. Definitive Positions of the Planets as seen from the Earth.

evening sky, it must pass through conjunction with the Sun. In Fig. 139, Venus is in conjunction with the Sun at *I* and *C*. Each month, as the Moon circles around the heavens, it passes through conjunction with all of the planets.

Opposition refers to the time when a planet is just opposite the Sun in the heavens. At opposition, a planet is 180° from the Sun and it is rising at sunset. Mercury and Venus can never be in opposition. In Fig. 139, Mars is in opposition at the point *O*.

Quadrature refers to the time when a planet is 90° from the Sun. Mercury and Venus can never be in quadrature. In Fig. 139, the points where Mars is in quadrature are marked *Q* and *Q′*.

The *sidereal period* of a planet is the time of its revolution about

the Sun from a place among the stars to its return to the same place again, as seen from the Sun. This is the true period.

The *synodic period* is the interval between two successive conjunctions with the Sun, as seen from the Earth.

If E is the period of the Earth, or one year, P the planet's synodic period, and S its sidereal period, the following relation holds:

$$1/S = 1/P - 1/E.$$

The Ptolemaic Theory. In classical times the Greek astronomers attempted to develop a theory which would represent the motions of planets on the constellation pictures of the night sky. As you read earlier, they thought it more reasonable to assume the big solid Earth stationary, and the apparently small and light heavenly bodies in motion; but in spite of this erroneous assumption the theory they developed represented the apparent motions of the planets quite well. The theory was put into very complete form by the Greek astronomer Ptolemy, who flourished in Alexandria about 150 A.D. It is known as the Ptolemaic theory of planetary motion.

To understand the fundamentals of the theory consider the planet Jupiter, which goes around the Sun in about twelve years. To represent the apparent motion of Jupiter in the sky, they assumed a long fictitious arm which turned about the Earth once in twelve years. It represented the main part of the apparent motion of Jupiter. To the end of this long arm they attached a shorter arm, which turned about the end of the long arm in one year. This motion of the short arm represented that portion of the apparent motion of Jupiter which is due to the motion of the Earth about the Sun in one year. Ptolemy assumed the Sun moved about at the end of a long fictitious arm, which turned about the Earth in the course of a year. Mercury and Venus moved on short arms, which were attached to the long arm, between the Earth and the Sun.

The motions of the longer arms and shorter arms were referred to as *cycles* and *epicycles* respectively. The Ptolemaic theory was accepted by scholars until after the time of Columbus, but by that time had become quite complicated.

The Copernican Theory. The astronomer Copernicus (1473-1543), became interested in the Sun-centered theory developed by the scholar Aristarchus about 1700 years earlier. The theory of

Aristarchus had been considered by Aristotle, but it was rejected by him and by later Greek scholars, including Ptolemy.

Copernicus became convinced that the Sun is the center of the solar system. The Sun-centered system is very much simpler than the old Ptolemaic. Also, it seemed more reasonable to assume that the Earth turned on its axis once a day than to assume that a big and distant object like the Sun swept about the Earth once every twenty-four hours.

Copernicus devoted his life to a full development of the Sun-centered theory, including new and more accurate tables for the planetary motions and published his work in a book entitled *De Revolutionibus Orbium Celestium.* However, he did not live to support and defend the theory after its publication. Later, Kepler and Galileo established the correctness of the Copernican theory.

Kepler's Laws. John Kepler (1571-1630), inherited many observations of the stars and planets made by the great observer, Tycho Brahe. Kepler was one of the great mathematicians of his century, and he spent twenty years of arduous labor determining facts of calculation, and developing laws from these facts and observations. Eventually he developed the three laws of planetary motion which have made him famous for all time. These laws are as follows:

1. *The planets move in elliptical orbits, with the Sun at one focus of the ellipse.* The ellipse is one of the conic sections shown in Fig. 53, on page 116.
2. *The motion of the planet is at such a speed that a line from the planet to the Sun sweeps over equal areas in equal intervals of time.* Fig. 55, on page 118, illustrates this law and shows how planets move faster when closer to the Sun.
3. *For any two planets, the squares of the periods of revolution are proportional to the cubes of their mean distances from the Sun.* Denoting the periods by P_1 and P_2, and the mean distances by a_1, and a_2, this law can be written

$$P_1^2/P_2^2 = a_1^3/a_2^3,$$

$$P_1 = P_2\sqrt{a_1^3/a_2^3}.$$

If the period is expressed in years, and the distance in astronomical units or the Earth's mean distance from the Sun, then P_2

and a_2 become unity. Dropping the subscripts, $P = \sqrt{a^3}$, a simple formula for the period of an object whose distance from the Sun is known.

Galileo, a contemporary of Kepler, had reached certain conclusions about bodies in motion from his experiments. Newton reduced these conclusions to three rather simple laws, which are known as Newton's Laws of Motion. They are as follows:

1. *Every body persists in state of rest or of uniform motion in a straight line unless it is compelled to change that state by a force impressed upon it.*
2. *The acceleration is directly proportional to the force and inversely to the mass of the body, and it takes place in the direction of the straight line in which the force acts.*
3. *To every action there is always an equal and contrary reaction.*

The Law of Gravitation. From these laws of motion, and from Kepler's laws of planetary motion, Newton worked out the law of gravitation which has been stated previously (page 286). It is as follows:

Every particle of matter in the universe attracts every other particle with a force that varies directly as the product of their masses, and inversely as the square of the distance between them.

Since the Moon is distant from the center of the Earth about sixty radii, the gravitational pull at that distance would be about 1/3600 that at the surface of the Earth. If f is the centrifugal force of a revolving body, v the velocity of the body, and r the distance from the center of motion, it is known that $f = v^2/r$. Calculation of the f for the motion of the Moon in its orbit gives a result agreeing with the calculation of the gravitational pull of the Earth at the Moon's distance. It is said that Newton checked the correctness of the law of gravitation by this calculation. Of course, nearly all predictions of astronomy since the time of Newton are based on this law, and their success shows the law to be correct.

Mass of Planet with Satellite. The mass of a planet can be determined more accurately if it has a satellite. In such cases, Kepler's third law, as revised by Newton, is used.

Newton showed that, for accuracy, the masses should be added to the formula as given earlier. If we apply Kepler's third law, as

revised by Newton, to satellites revolving about the planets, and denote by m_1 the mass of the first planet plus the mass of its satellite and by m_2 the mass of the second planet plus that of its satellite; the periods of revolution of the satellites by p_1 *and* p_2 respectively; and the mean distances of the satellites from the planets by a_1 and a_2 respectively, the following formula results:

$$m_1 p_1^2 / m_2 p_2^2 = a_1^3 / a_2^3.$$

Let us suppose that we desire to obtain the mass of a planet and its satellite in terms of the mass of the Earth-Moon system. By observing the satellite, its period of revolution and its distance from the planet can be obtained. These are p_1 and a_1. For p_2 and a_2 we use the period of revolution and distance from the Earth of our Moon. The preceding formula solved for m_1 becomes:

$$m_1 = m_2 p_2^2 a_1^3 / p_1^2 a_2^3.$$

Everything is known but m_1, and substitution of the known values in the formula gives the value of m_1.

Mass of Planet without Satellite. If a planet does not have a satellite, the determination of its mass is more difficult. This is the case for Mercury, Venus, and Pluto. If nothing disturbed the motion of a planet, it would move about the Sun in an elliptical path according to Kepler's laws. However, each planet does pull on the others.

Mercury is so small, and so close to the Sun, that it pulls Venus out of its regular orbit very little and the Earth and other planets even less. The mass of Mercury must be calculated from these small effects, so that it is not known with accuracy.

Venus pulls the Earth and Mercury out of their orbits by small amounts, and it pulls Mars out of its path by a still smaller amount. From accurate observations and careful calculations on the orbits of Mars, the Earth, and Mercury, the amount Venus pulls these planets out can be determined, and from the law of gravitation the mass of Venus can be calculated. Since Venus is much more distant from Mercury, the Earth, and Mars than any satellite is from the planet about which it revolves, these effects are small, and the mass of Venus cannot be determined with the accuracy which would be possible if it had a satellite. However, the mass of Venus is more accurately known than the mass of Mercury.

Pluto, the outermost planet, pulls Neptune, the next planet, out

of its orbit appreciably, and its mass can be calculated from the effect. To show the great amount of labor involved when this method is used, let us consider the calculation of the mass of Pluto in more detail.

The first step in the process was a study of the observations of Neptune, the planet closest to Pluto. This work was done at the U. S. Naval Observatory. The observations of Neptune, from the accidental prediscovery observations in 1795 down to 1938, were revised using the best possible modern star positions. For the older observations, in some instances, this made a considerable change. The next step was the calculation of the position of Neptune for the time of each of those observations, and the forming of the difference between the observed position and the computed position.

The differences, or residuals, were sent to Yale where the next step was taken. From these residuals, corrections to elements of Neptune's orbit and also the mass of Pluto, were solved for, to reduce the residuals to negligible quantities. It was found that the older figures for the orbit of Neptune were changed very little, and that the mass of Pluto must be just about the same as the mass of Venus. The uncertainty in the mass of Pluto was calculated as about one-eighth. As time goes on, more observations of Neptune and of Pluto will be secured, and the mass of Pluto can be calculated with greater accuracy.

The Planetary Orbits. You have read earlier that the orbits of the planets are ellipses, with the Sun at one focus. The ellipse is one of the conic sections shown in Fig. 53 on page 118. The other conics, or possible orbits, as explained there are the circle, the parabola, and the hyperbola, The eccentricity of an orbit is the elongation, or the deviation from the circle. It is zero for a circle, and it is considered unity if the far end of an ellipse is stretched out to an infinite distance. The orbit then becomes a parabola. The eccentricity of a hyperbola is greater than unity.

For the principal planets the eccentricity is quite small, that is, the orbits are nearly circular. For only two, Mercury the innermost, and Pluto the most distant, is the eccentricity as much as one-tenth. For the minor planets, the planetoids or asteroids, the eccentricity is higher, occasionally exceeding five-tenths, but even these orbits are much less elongated than the orbits of comets. For comets,

the eccentricity of the orbit is usually between nine-tenths and unity.

Elements of the Orbits. The orbit of a body in the solar system is fixed by certain numerical quantities referred to as elements. The semi-major axis, *a*, defines the size of the orbit. (See Fig. 140.)

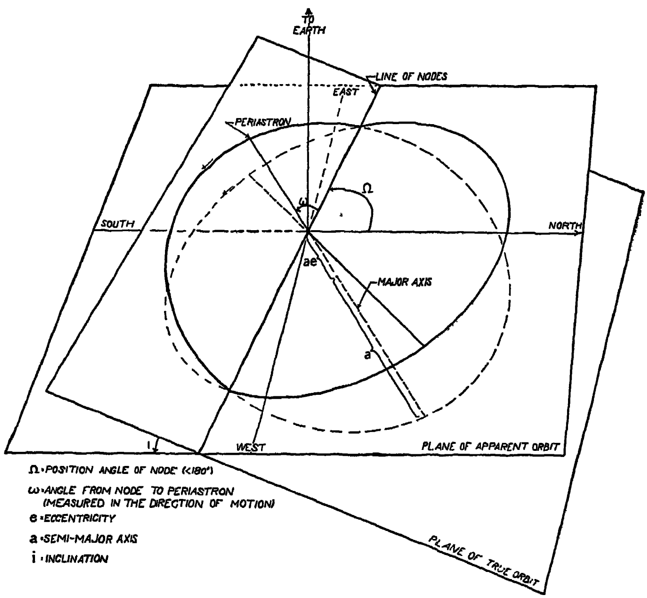


FIG. 140. Elements Defining the Orbit of a Body in the Solar System

The eccentricity, *e*, defines its shape. The inclination to the ecliptic, *i*, and the longitude of the ascending node, ☊, fix the plane of the orbit. The angle ☊ is measured along the ecliptic from the equinox to the intersection of the orbit of the planet with the ecliptic, the intersection at which the planet is passing from south to north.

The position of the orbit in this plane is defined by the so-called "longitude of perihelion, π (not shown in the figure)." The angle π is a peculiar angle, being the sum of the angle ☊ mentioned previously and measured in the plane of the ecliptic, and the angle ω measured from the intersection of orbit of the planet, and in the orbit of the planet, on to its perihelion point. Thus π is a continuous angle, but counted in two planes.

Two more elements are necessary, first the sidereal period P, which can be obtained from the semi-major axis a, as explained previously, and second, the position of the planet at some starting point or epoch, E.

Surface Gravity. The law of gravity is stated on page 286. If g is the surface gravity and r the radius of another planet, m the mass in terms of the Earth's mass, G the surface gravity, and R the radius of the Earth, substitution in the formula for gravitation gives

$$g = (mR^2/r^2)G.$$

From the mass and the radius of any planet the surface gravity as compared with that at the surface of the Earth can be computed readily, using this formula.

Density is mass per unit of volume. Suppose d is the density, M the mass, and r the radius of another planet; D the density, E the mass, and R the radius of the Earth. It follows that

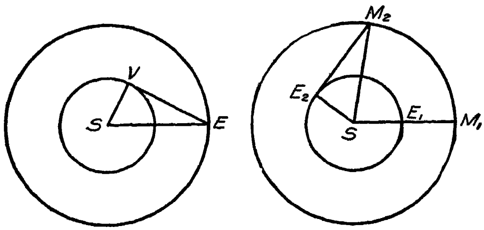
$$d = (M/E)(R/r)^3D.$$

Rotation. The rotation of the planet Mars can be determined accurately from definite and permanent markings on the solid surface. For the planets Jupiter and Saturn, distinct atmospheric, or cloud, markings are available. These give a good result, the accuracy being a little less than that attained with permanent markings. For Uranus and Neptune, the spectroscope can be used. For Mercury, surface markings seen indistinctly are used, leaving the result in doubt. For Venus, indistinct cloud markings leave the result in doubt, even more than for Mercury. For Pluto, no information whatever is available.

Determining Sizes of the Planetary Orbits. The distance of a planet from the Sun in terms of the Earth's distance could be obtained approximately even before the days of the telescope. Taking the planet Mars, for example, the interval from a rising in the east at sunset until it rises again in the east at sunset is the synodic period. From this, and the time it takes the Earth to go about the Sun the sidereal, or true, period for the revolution of Mars about the Sun is readily obtained. (See page 319.) This is found to be 687 days. At intervals of 687 days, therefore, Mars is at the same place in its orbit. From the known motion of the Earth about the Sun, the place of the Earth at each of those times is known, and

observations of Mars give the direction of Mars from the Earth at each of those times.

For a planet outside the orbit of the Earth, as Mars, the date of *opposition*, that is, the date when the planet is exactly opposite the Sun, can be noted. The position of Mars then is M_1 in Fig. 141. Then the next date when the planet is at *quadrature*, or 90° from the Sun, M_2 is noted; the Earth is then at E_2. From the sidereal period of Mars the angle M_1SM_2 is known, and from the sidereal period of the Earth the angle E_1SE_2 is known. The difference of the two



VENUS MARS

Fig. 141. Basis for Computing the Size of Planetary Orbits

angles is M_2SE_2, or an acute angle of the triangle with the right angle at E_2. The ratio of the distance of the Earth from the Sun, E_2S, to the distance of Mars from the Sun, M_2S, is cos M_2SE_2, and is, therefore, known.

For the inner planets, Mercury and Venus, a more simple observation indicates the size of the orbit as compared to the orbit of the Earth. Assuming the orbits to be circles, Fig. 141, it is evident that when one of these planets appears farthest from the Sun, *SVE*, the angle at the planet between the Earth and the Sun, must be 90°. If *VES*, the angle between the planet and the Sun at that time as seen from the Earth, is measured, an acute angle of a right-angled triangle is obtained. If a right-angled triangle is constructed with one of the angles equal to the measured acute angle, a triangle similar to triangle *ESV* results. The radius of the orbit of the Earth, *SE*, corresponds to the hypotenuse of the right triangle, and the radius of the orbit of the planet, *SV*, corresponds to the side opposite the measured acute angle.

This triangle gives the ratio of the radius of the orbit of the planet to the radius of the orbit of the Earth. The orbits of the planets are not perfectly circular, and so this method requires a modification which, however, is simple mathematically.

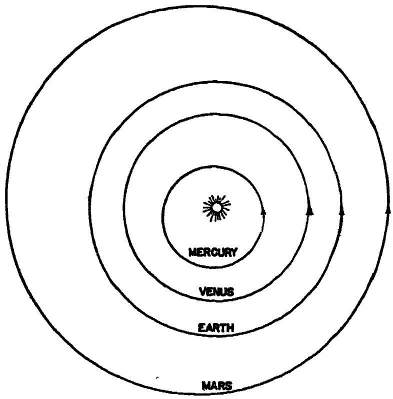


FIG. 142. The Orbits of the Inner Planets. (From Wylie's *Our Starland*, Lyons and Carnahan.)

Modern methods of orbit calculation are more accurate than the preceding methods, and one of the "elements" of the orbit as calculated is the mean distance of the Earth from the Sun.

From the known orbit of a planet, the distance from the Earth at any time can be calculated in terms of the Earth's mean distance

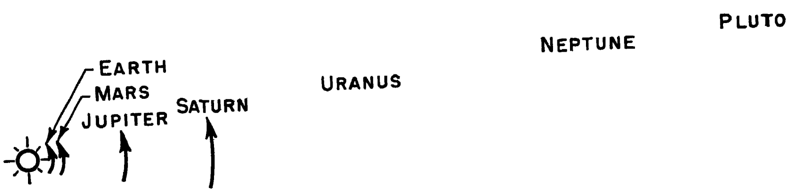


FIG. 143. The Relative Distances of the Outer Planets

from the Sun. If, therefore, when some planet is relatively close to the Earth, the distance from the Earth is measured in miles or kilometers, the distance of the Earth from the Sun in miles or kilometers, is known. For example, the distance of Venus from the

Sun is known to be about 0.72 times that of the Earth from the Sun, so when Venus is closest to the Earth, that is, between the Earth and the Sun, the distance of Venus from the Earth must be about 0.28 times the distance of the Earth from the Sun. If that distance is measured in miles, the distance of the Earth from the Sun can be expressed in miles. Since the orbits of all the other planets are determined with respect to the Earth's orbit, the absolute size of all the other orbits in the solar system is known as soon as that of the Earth is known. Fig. 142 and Fig. 143 illustrate the relative sizes of the planetary orbits.

Diameters from Transits of Venus. The English astronomer, Edmund Halley (1656-1742), famous for predicting Halley's Comet and one of the early directors of Greenwich Observatory, suggested using transits of Venus for getting the scale of the solar system. In 1677 he pointed out that Venus occasionally passes across, or *transits*, the face of the Sun. At such times Venus is so close that if its position is observed from widely separated points on the surface of the Earth, its distance can be calculated from the difference in position as seen from two such points.

Following this suggestion by Halley, expeditions have been sent to all parts of the World to observe the four transits of Venus which have occurred since. These were in the years 1761, 1769, 1874, and 1882. Halley's method was the best available for two hundred years after he suggested it, but a better method is in use now.

Diameter from Observations of Asteroids. Several minor planets (asteroids or planetoids) come closer to the Earth than Venus ever can. The first such asteroid discovered was Eros, which can come within less than fourteen million miles of the Earth. At close approaches, it remains closer than Venus for several weeks, and it can be observed accurately by astronomers all over the world on every clear night during the period that it remains close. Furthermore, Eros appears as a mere point of light in the telescope. Its position can be observed somewhat more accurately than that of Venus, even when Venus is seen projected on the Sun's disk.

Among advantages of the newer method are: observations can be extended over several weeks instead of only for a few hours; the asteroid comes much closer to the Earth than Venus ever does, making the parallax angles larger and easier to measure; the asteroid is seen as a mere point of light permitting more accurate

settings; measures on the asteroid can be made at established observatories, while the transit of Venus method requires expeditions similar to eclipse expeditions, which sometimes fail because of clouds.

The following table gives for each of the nine planets, distance from the Sun; sidereal period, or the planet's year; the mean diameter; the period of rotation, or the planet's day; the number of known satellites. The figures are taken from the 1943 *American Ephemeris and Nautical Almanac*, with the exception of the figures for Pluto, the most recently discovered planet. As the observations available for that planet cover only a small part of its orbit, the orbital elements are revised as new information is secured. For this planet, newer data than that in the 1943 *Ephemeris* has been used. To make the memorizing of the table easier, the figures have been rounded off.

TABLE XIII. THE PRINCIPAL PLANETS

Name of Planet	*Signs of the Planets*	*Distance from Sun in Millions of Miles*	*Sidereal Period of Revolution*	*Mean Diameter in Miles*	*Period of Rotation*	*Number of Satellites*
Mercury	☿	36	88 d.	3,000	88 d. ?	0
Venus	♀	67	225 d.	7,600	20–30 d.	0
Earth	⊕	93	365¼ d.	7,918	$23^h\ 56^m$	1
Mars	♂	142	687 d.	4,200	$24^h\ 37^m$	2
Jupiter	♃	483	12 yr.	87,000	$9^h\ 50^m$	11
Saturn	♄	886	29½ yr.	72,000	$10^h\ 14^m$	9
Uranus	♅	1780	84 yr.	31,000	$10^h\ 45^m$	4
Neptune	♆	2790	165 yr.	33,000	$15^h\ 48^m$	1
Pluto	♇	3670	248 yr.	7,600	?	0

EXERCISES

1. What is a planet? How are planets different from stars? Name the known planets in the order of their distance from the Sun.
2. What is Bode's law? Which planet is an "interloper" by this law?
3. What is an asteroid? How was the first asteroid discovered?
4. Describe the apparent motion of a planet in the sky.
5. What are the planetary configurations? Explain.

6. Find the synodic periods of Mars and Venus if their sidereal periods are 687 days and 225 days respectively.
7. Find the sidereal periods of Mercury, and Uranus if their synodic periods are 116 and 369.7 days respectively.
8. Can you explain why Mars and Venus have the longest synodic periods of all the planets? (Notice the formula used in question 6.)
9. State Kepler's three laws of planetary motion.
10. Calculate from the period and distance of the Moon the period of a satellite revolving 4000 miles from the center of the Earth.
11. Calculate the period of Jupiter from its distance from the Sun, and from the period and distance of the Earth from the Sun.
12. State Newton's laws of motion and his law of gravitation. Write the latter algebraically.
13. What is the ratio of the mass of Jupiter to that of the Earth-Moon system if satellite IV is 1,200,000 miles from Jupiter, and its period is 17 days?
14. Saturn's mass is 95 times the mass of the Earth and its diameter is 72,000 miles. What is the force of gravity at its surface?
15. Explain how the masses of Pluto, Mercury, and Venus have been calculated.
16. What connection do the conic sections have with the orbits of the planets?
17. Identify and define the elements of the orbit of a planet. What are the values of four elements of the Earth's orbit?
18. Find the relative distance of Mercury and the Earth if Mercury's greatest elongation is 23°.
19. What is the approximate length of the base line if Mars is observed at the same real point in its orbit after a 687-day interval?
20. Write Table XII from memory.

☆ XVI ☆

The Planets Themselves

The Inner Planets

Mercury is the smallest (see Fig. 144, page 332), the hottest, the closest to the Sun, and the fastest moving of the planets. Its diameter is about 3000 miles; its mass, which is uncertain, is about one-twentieth the mass of the Earth; its rotation period probably is the same as its period of revolution, that is, it keeps the same side toward the Sun; its period of revolution is 88 days; it has no satellite.

Mercury is visible to the naked eye only a few weeks each year. This is not because it is too faint to be seen easily, but because Mercury is so close to the Sun. Ordinarily, when in the evening sky, it sets before twilight is over, and when in the morning sky, it does not rise until after dawn. To be well above the horizon when the stars are visible, Mercury should be near greatest elongation, and at a greater than average distance from the Sun.

In the evening sky in March, Mercury is where the Sun will be in May, which is well to the north, and sets later. If Mercury is, let us say, 24° from the Sun at any time from February to early June, it will not set until after the stars are easily visible. In the Autumn months, however, in the evening sky Mercury is farther south than the Sun. Going south means an earlier setting, and so, from August to early December, Mercury in the evening sky, even if at greatest elongation, sets before the stars are visible.

Ordinarily, Mercury is about as bright as the brightest stars in that part of the sky. For example, in early February, 1941, Mercury was a little brighter than Vega or Capella. In early June, 1941, when in better position for observation, it was conspicuous but not quite so bright, the brightness at that time being between that of Rigel and Altair.

Mercury is so small that it could hardly hold an atmosphere, and observation indicates there is no appreciable atmosphere. Because Mercury is always quite near the horizon after the stars have

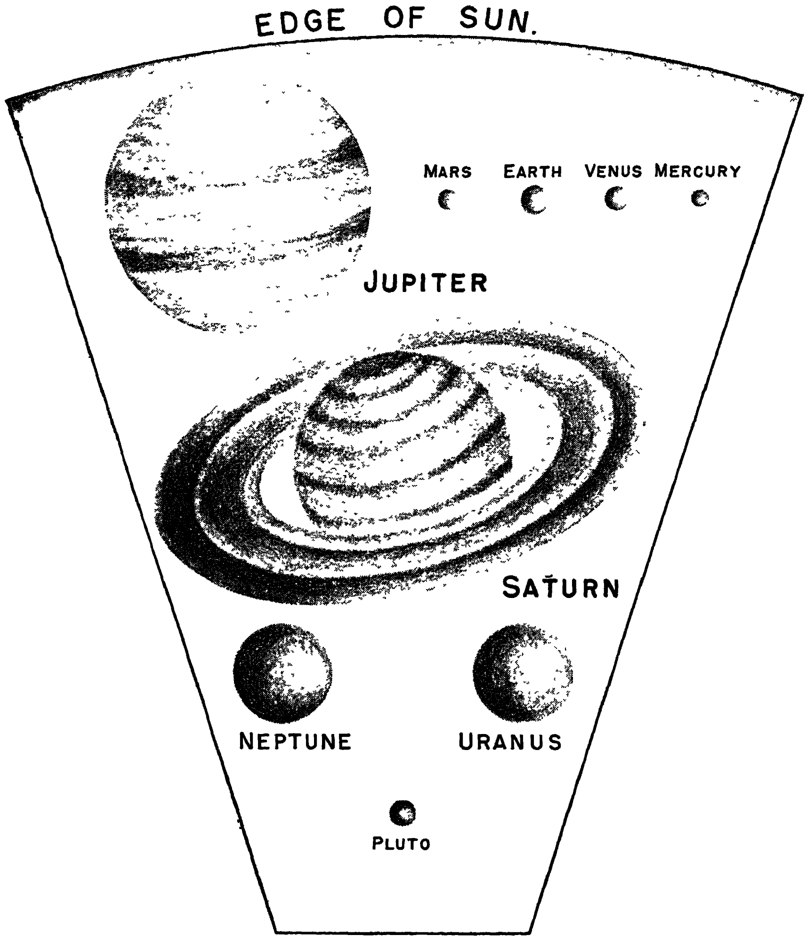


FIG. 144. The Relative Size of the Sun and Planets

appeared, telescopic observation by night is practically impossible. The only useful telescopic observations of Mercury, therefore, are those made in broad daylight when the planet is high in the sky. Under these conditions it is very difficult to see any detail. The

best observers are agreed, however, that the planet probably keeps the same side toward the Sun, or rotates once in 88 days. The temperature can be determined with more certainty than the rotation, and on the sunward side, the temperature is high enough to melt lead.

Transits of Mercury. Since Mercury is closer to the Sun than the Earth, at every revolution it passes almost between the Earth and Sun. Occasionally, it passes directly across the face of the Sun. This is called a *transit* of Mercury. At the time of a transit, the position of Mercury with respect to the Sun and the Earth is determined very accurately. Astronomers who work on orbits and positions of the planets are interested in obtaining accurate timings of the beginnings and endings of these transits.

Transits of Mercury are useful not only in making possible more accurate predictions of the position of Mercury, but also in giving a more accurate value of the mass of Venus, in checking the effect on the motion of Mercury predicted by the relativity theory, and in checking the slow lengthening of our own day indicated by calculation of the friction of tides.

Transits of Mercury, although not frequent, occur much more often than transits of Venus. Between now and the year 2000 there are no transits of Venus, but there are seven transits of Mercury. These are as follows:

November	13	1953
May	5	1957
November	6	1960
May	9	1970
November	9	1973
November	12	1986
November	14	1999

Venus can come closer to the Earth than any other planet. It is brighter than any of the stars and brighter than any other planet. Its diameter is about 7600 miles (see Fig. 144, page 332); its mass is about eight-tenths that of the Earth; its rotation period is uncertain, but probably twenty to thirty of our days; its period of revolution is 225 days; it has no satellite. Venus is sometimes called the Earth's twin sister, since it is about the same size. It has considerable atmosphere; the temperature apparently is such as to permit

life; it appears to rotate on its axis although the length of day is uncertain.

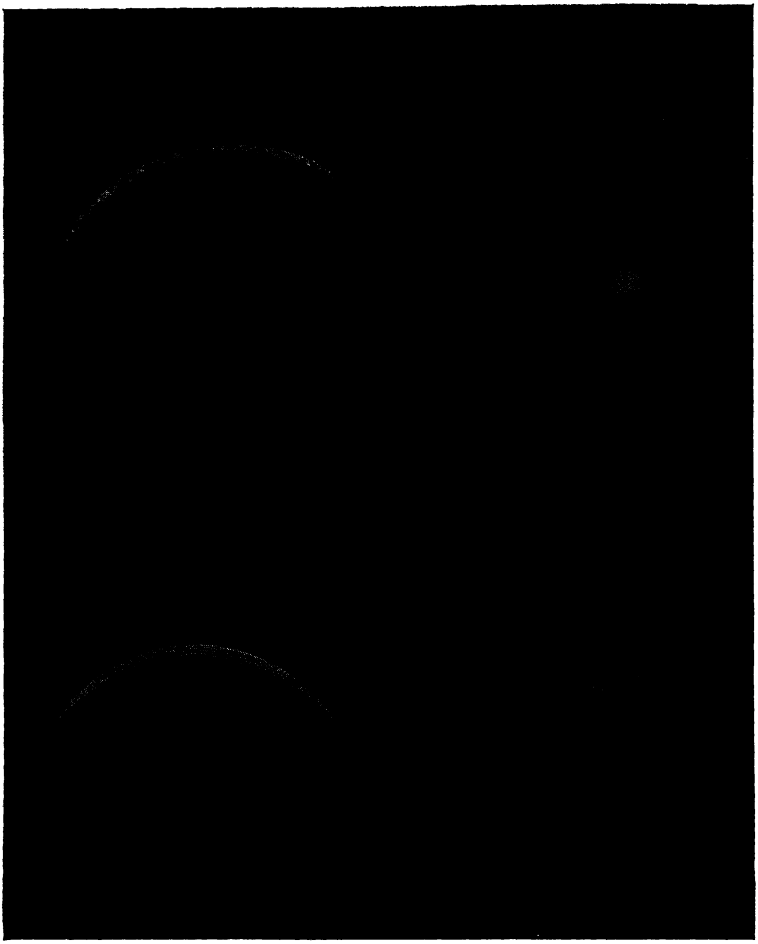


FIG. 145. Changes in the Apparent Shape and Size of Venus. Photograph from Lowell Observatory

The Atmosphere of Venus. This has been studied with powerful spectroscopes attached to the 100-inch telescope at Mount Wilson. No appreciable water vapor has been found, but this test is not

very sensitive. It is certain, however, that the water vapor content is only a small fraction of that in the Earth's atmosphere. No appreciable oxygen has been found either. The oxygen test is more sensitive, and this probably means that the free oxygen in the atmosphere of Venus is less than 1/1000 that in the Earth's atmosphere. A surprising result is that there is a relatively enormous amount of carbon dioxide in its atmosphere.

Since no definite detail can be seen, the *rotation period* cannot be determined with any certainty from markings. It is too slow for determination with a spectroscope, so the period is very uncertain. The results from cloud markings, as far as they go, suggest a period of twenty to thirty days.

Daylight Visibility of Venus. The planet Venus is unique in being the only planet visible to the naked eye in broad daylight. When near greatest elongation (not greatest brilliance) (see Fig. 144, page 332), and when it crosses the meridian reasonably high in the sky, Venus can be seen readily with the naked eye on clear days. When near greatest elongation as an evening star, it crosses the meridian at about three o'clock in the afternoon, and under good conditions may be seen easily with the naked eye from two o'clock on. When near greatest elongation as a morning star, it crosses the meridian at about nine o'clock in the morning, and under good conditions may be seen readily throughout the forenoon until about eleven o'clock. Good elongations of Venus for daylight visibility occur every few years.

Transits of Venus. You have read earlier that the English astronomer Halley suggested that transits of Venus across the face of the Sun be used for getting the diameter in miles of the orbits of the various planets in our solar system. Halley even suggested places and equipment for observing the transit of 1761. Of course, he did not expect to observe that transit personally, for that would have meant living to the ripe old age of 105. Because of the high standing of Halley, and the obvious merit of his suggestion, the British Government and others sent parties to distant parts of the World to observe the transit of 1761. Expeditions were sent to St. Helena, Cape of Good Hope, India, and elsewhere. For the transit of 1769, expeditions were sent even farther.

Mars, the Most Studied Planet. Mars is the only planet of which the real land surface can be seen. It does not come as close to the

Earth as Venus, but when closest it is at full phase, just opposite the Sun and in good position for viewing. Its diameter is about 4200 miles (see Fig. 144, page 332); its mass is about one-tenth that of the Earth; its period of rotation is 24 hours 37 minutes; its period of revolution is 687 days; it has two satellites.

Mars can vary enormously in distance from the Earth. It can come as close as 35 million miles, and it can get more than 245 million miles from the Earth. Mars is closest to the Sun when outside of the place where the Earth is in late August. The Earth is farthest from the Sun in early July, so when Mars is rising at sunset or at opposition, anywhere from July to early October, it is relatively close to the Earth.

Favorable Oppositions. Oppositions (see Fig. 139, page 318) which bring Mars relatively close to the Earth are the most favorable times for studying the planet. In general there are two or three favorable oppositions in succession, and then another series of favorable oppositions about fifteen years later. A very favorable one occurred in late August in 1924, and a good one in early November 1926. A favorable opposition occurred in late July, 1939, and another in early October, 1941. The next favorable opposition should occur about 1954.

With the great change in distance, the brightness of Mars varies enormously. For example, at the favorable opposition of August, 1924, the magnitude was −2.7, definitely brighter than Jupiter ever gets. In November, 1938, when Mars was at a considerable distance from the Earth, the magnitude was only +1.9, or about as bright as the stars in the belt of Orion.

The change in the brightness of Mars in only a few months may be considerable. For example, in early April in the year 1941 the brightness of Mars was the same as that of Altair. By the latter part of May it had become as bright as Vega or Capella. By the latter part of August the brightness was equal to that of Sirius, and by early September the brightness was equal to that of Jupiter. In early October, 1941, a rather favorable opposition, the magnitude of Mars was −2.4, brighter than Jupiter at that time, and about as bright as Jupiter ever gets.

The Physical Nature of Mars. Mars is unique in that it is the only planet on which the real land surface can be seen well enough to map permanent markings. This is possible because of its closeness, which is next to Venus; the fact that the air is rather thin,

and the fact that when closest the planet is at full phase, being just opposite the Sun.

The axis of Mars is tipped to the plane of its orbit a little more than that of the Earth, about 24° 50′. Hence, Mars has seasons as

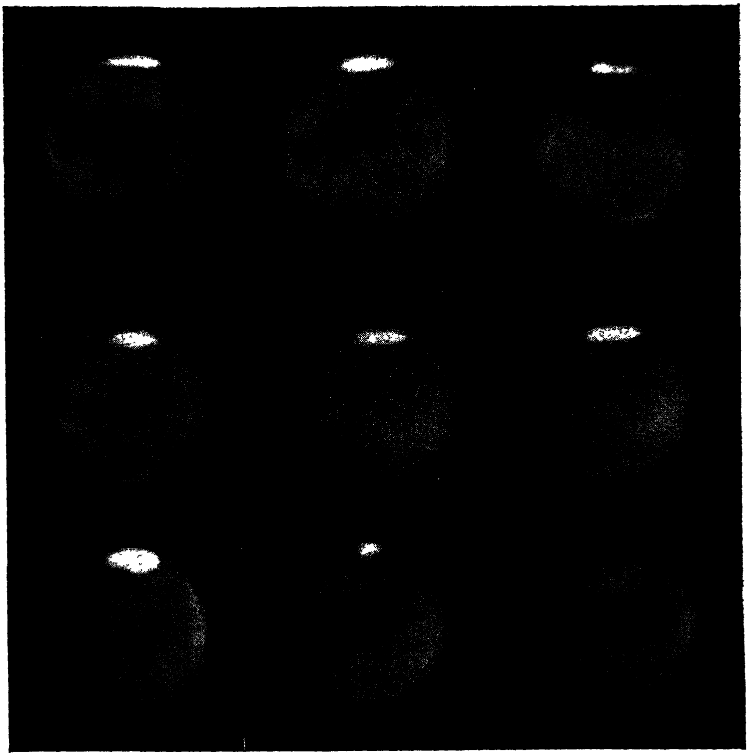


FIG. 146. Mars. The upper row shows three different faces of the planet. The middle row shows variations on three successive nights of the polar cloud cap in Autumn. The bottom row shows the melting of the polar snow cap, and the growth of dark areas, presumably vegetation, during summer

the Earth does. Mars has a polar cap, presumably of snow or frost, which covers a considerable area in the Martian Winter and diminishes to almost nothing in Summer. In the Martian Spring, certain areas take on a bluish or greenish tinge suggesting vegetation. In Summer and Autumn they turn to a yellowish or brownish and eventually to a grayish color.

With the 100-inch telescope, temperatures can be determined for

relatively small areas on the surface of Mars. In the equatorial regions of Mars the temperature rises to that of a cool summer day on the Earth, but the temperature drops far below freezing every night, which is what might be expected with a thin atmosphere.

It has been estimated that the density of the air at the surface of Mars is about equivalent to that of the Earth eleven miles up.

FIG. 147. The Polar Cap of Mars in Martian Winter (left) and Martian Summer (right). Arrow 1 points to the same marking in the two pictures, and arrow 2 points to the limit of the polar cap

Neither oxygen nor water vapor can be detected with powerful spectroscopes. There may be a small amount of water vapor because, as you have read in the paragraphs on Venus, this test is not very sensitive. As the polar caps appear to be snow, there probably is some water vapor in the atmosphere of Mars. The test for oxygen is sensitive, however, and the amount of free oxygen in the atmosphere, must be less than one-thousandth that in the atmosphere of the Earth.

It has been suggested that on Mars, with very little plant life and presumably with a small supply of oxygen to start with, much of the oxygen has been going into the rocks, where it is lost, until now very little is left. This hypothesis is in agreement with the observed fact that the deserts of Mars are reddish in color, suggesting oxidation of rocks.

The Satellites of Mars. The two satellites of Mars are interesting as among the fastest moving in the solar system. The inner one,

Phobos, completes a revolution in 7 hours, 39 minutes, or less than a third of the Martian day. It is the only satellite with a period less than the planet's day. It rises in the west and sets in the east, going through its phases as it moves across the sky. For example, it may rise in the west just after sunset, as a crescent new moon, and later in the same evening may be seen as a full moon. It will set in the east 5 hours 30 minutes after rising in the west.

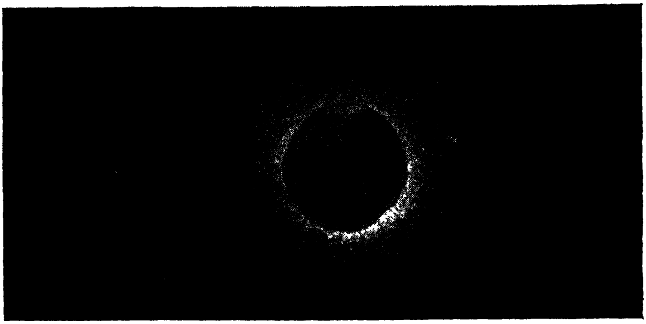


FIG. 148. Mars, and its Satellites, Phobos to right and Deimos to left. Photograph from Lowell Observatory

The outer moon, Deimos, has a period of revolution of 30 hours 18 minutes. Since its period of revolution, or "month," is longer than the Martian day, it will rise in the east as our Moon does, but go across the sky very slowly, going through all its phases twice before setting two and one-half days after rising.

Phobos, the inner moon, would look about a third the size that our Moon appears to us. At its brightest, it would be about halfway between our Moon and Venus. The outer moon, Deimos, would look so small that human beings would not be able to see its phases with the naked eye from the surface of Mars. At its brightest, Deimos would look a little brighter from the surface of Mars than Venus does to us.

THE ASTEROIDS, OR PLANETOIDS

You have read already about the discovery of Ceres, the first asteroid known, and of some of the other larger asteroids. Since the application of photography to astronomy, several asteroids have been discovered every year. Those for which an orbit is computed are given numbers, and by 1941, there were 1513 numbered

asteroids. A study of photographs made with the 100-inch Mount Wilson telescope (in 1938) indicated that the total number of asteroids photographed was about thirty times the total of the numbered asteroids. This indicated that there are about 40,000 asteroids brighter than magnitude nineteen, the limit on those photographs.

Formerly, it was stated in textbooks that the asteroids were between the orbits of Mars and Jupiter. With powerful telescopes, however, the belt has been broadened greatly. The great majority are between Mars and Jupiter, but some cut inside the orbit of Venus, and one goes out almost to the orbit of Saturn.

Several asteroids are now known which go around at the same distance from the Sun as Jupiter, so that the Sun, Jupiter, and the asteroids form practically an equilateral triangle. It can be worked out from the law of gravitation that if a small body gets reasonably close to the point in space forming an equilateral triangle with two much larger bodies, it will tend to fall toward that point to complete the triangle. This was worked out by the French astronomer Lagrange, about 1780, and more than a hundred years later asteroids illustrating this fact were found.

The first asteroid found to come inside the orbit of Mars, is Eros. This asteroid can come within 13,500,000 miles of the Earth, and, as you have read before, it is used for accurate determinations of the scale of the solar system. The period of Eros is 1.75 years, or less than that of Mars.

In recent years some asteroids have been found which can come inside the orbit of the Earth, and even inside the orbit of Venus. (See Fig. 154, page 355.) Two of these can make very close approaches to the Earth.

The diameters of the brightest, presumably the largest, asteroids have been measured. Some of these are Ceres, 480 miles; Pallas, 300 miles; Vesta, 240 miles. From the brightness, it has been estimated that about 160 have diameters exceeding fifty miles. Eros may be fifteen miles in diameter, while many are less than a mile in diameter, mere "mountains broken loose."

As telescopes become more powerful, asteroids which are smaller and which make closer approaches to the Earth are being found. This suggests that eventually an object not very different from that which formed Meteor Crater in Arizona may be found. As you will

read later in the chapter on meteors, the orbits of the spectacular meteors are found to be similar to those of the asteroids, such as Adonis, which come inside the orbit of the Earth. Perhaps the large stone-dropping meteors are merely members of the asteroid group which are too small to be seen with present telescopes.

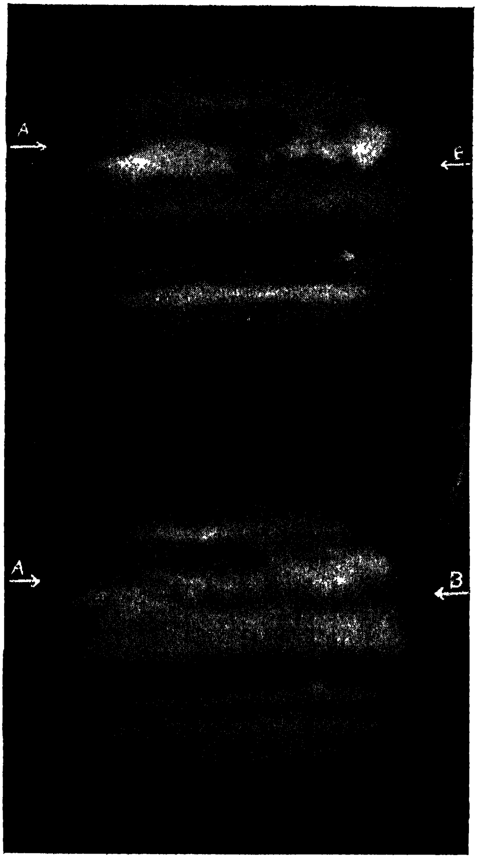


FIG. 149. Jupiter. Photographs showing change in relative position of spots A and B in two days. Photograph from Lowell Observatory

THE LARGEST PLANETS

Jupiter. This is the largest planet (see Fig. 144, page 332) and the heaviest one, being larger and heavier than all the other planets combined. It is the fastest rotating, has the most known satellites,

and is the brightest of the planets except Venus. Because of its size, more detail can be seen on its surface than for any other planet in spite of its distance. Its diameter is 87,000 miles; its mass is 317 times that of the Earth; its rotation period is 9 hours 50 minutes, but, since the surface is made up of clouds floating in the atmosphere, the period of rotation varies with the latitude. The period of revolution is twelve years; eleven satellites are known. Since the solid surface cannot be seen, the measured diameter includes most of the atmosphere, and the rotation is determined from the cloud markings. These markings are seen easily in a small telescope.

Jupiter and all the outer planets are very cold, about −200° C according to measurements. The spectroscope shows plenty of methane (fire damp) and ammonia present in the atmosphere. The temperature is such that the ammonia probably is a sort of "snow" in the atmosphere, and the chief constituent of the clouds.

The Constitution of Jupiter. From the rate of rotation, and the flattening, the weight of Jupiter must be highly concentrated toward the center. Putting the available information together, the rocky core of Jupiter appears to be about 43,000 miles in diameter. This should be similar to the solid part of the Earth. Outside of this is a layer of ice some 16,000 miles deep, and outside of this a layer some 6,000 miles deep consisting of hydrogen and its compounds, including methane and ammonia. Because of the cold and the weight of the outer layers, most of the hydrogen would be solid, or liquid. The ammonia would be solid. Only the outer few hundred miles of this layer would be gaseous, the atmosphere in which the clouds of ammonia "snow" float.

The "great red spot," which has been watched since 1878, cannot be attached to the solid surface of Jupiter, for its rate of rotation changes. Presumably the solid nucleus of Jupiter rotates uniformly. The great red spot must have drifted over an east and west distance of some 40,000 miles, and over many thousands of miles in latitude. It is too permanent to be a cloud, so it may be a great "berg" of frozen ammonia floating in an "ocean" of liquid hydrocarbons.

The Satellites of Jupiter. Jupiter has eleven known moons, which astronomers refer to by number, rather than by name. Four of these were discovered by Galileo. As they are of fifth and sixth

magnitude, they are seen easily with field glasses of sufficient power to separate them from the glare of the bright planet itself. The fifth moon discovered was of magnitude thirteen. It requires a powerful telescope to see an object of that magnitude close to

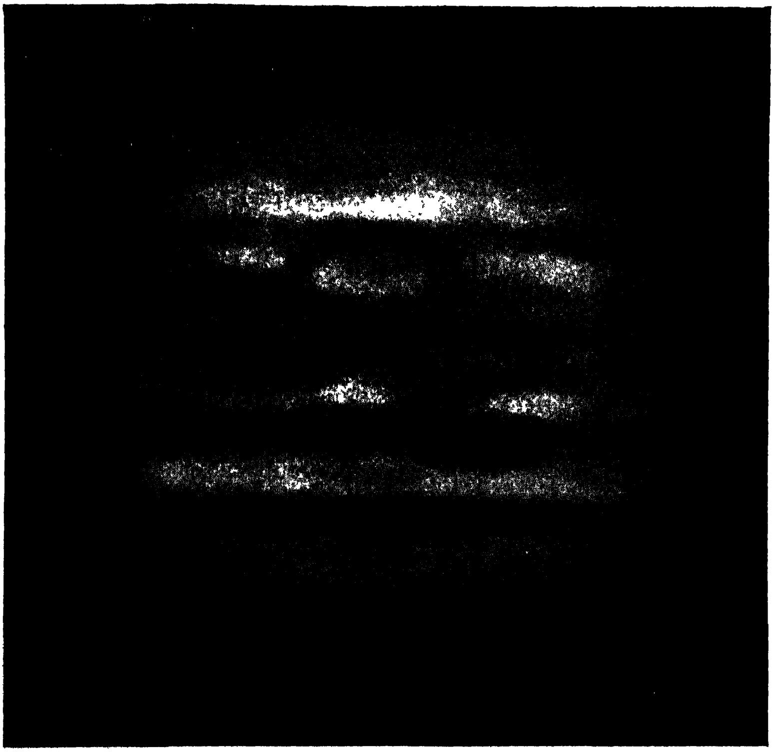


FIG. 150. Jupiter. The Great Red Spot is above center. At the right, Satellite I shows as a bright dot and its shadow as a dark dot

such a bright planet as Jupiter, and that moon was not discovered until 1892, with the 36-inch Lick telescope.

Since that time, six more moons have been discovered, all by photography. The last two, the tenth and eleventh, were discovered on photographs made with the 100-inch telescope in 1938. The six outer moons vary in magnitude from fourteen to nineteen, and are arranged in two groups. The sixth, seventh, and tenth, revolve directly, at a distance of about seven million miles, while the elev-

enth, eighth, and ninth move in retrograde orbits (moving in the reverse direction), at about twice that distance from Jupiter.

Saturn. This is the most distant and the slowest moving of the naked-eye planets. It is the most remote of the planets known to the ancients. Saturn is next to Jupiter among the planets in size (see Fig. 144, page 332), mass, and speed of rotation. Including its atmosphere, it is made of the lightest materials. It is unique among the planets in having a system of rings which revolve about it. The rings make it the most interesting of the planets as viewed through the telescope. Its diameter is 72,000 miles; it mass is ninety-five times that of the Earth; its rotation period is 10 hours 14 minutes; its period of revolution is 29½ years; in addition to its ring system, it has nine known satellites.

Since Saturn is nearly twice as far away as Jupiter, the cloud markings are harder to see, but occasionally a spot appears which is large enough to be seen distinctly. From such spots the rotation can be determined with fair accuracy. For example, a white spot appeared in 1876 and continued visible for some weeks. A similar white spot appeared in 1933.

Saturn is like Jupiter in having a very deep atmosphere, and its average density is even lower than that of Jupiter. In fact, if it could be placed, atmosphere and all, in an enormous basin of water, it would float. It is massive enough to hold the light substances. There must be plenty of such light substances as hydrogen, and a deep atmosphere, to give it the low density.

The Satellites of Saturn. Saturn has nine known moons, five of which were discovered before 1700 and are observable in telescopes of modest size. They are not so easily identified as the satellites of Jupiter, which are seen in a straight line, but they can be identified from information given in the *American Ephemeris and Nautical Almanac.* The four additional satellites were discovered, two by Herschel in 1789, another by Bond of Harvard in 1848, and the ninth by Pickering of Harvard in 1898. This outer moon of Saturn, like the three outer moons of Jupiter, moves in a retrograde, or backward direction.

The Rings of Saturn. The most interesting feature of Saturn is its ring system, really a triple-ring system. The diameter of the outer portion of the ring system is about 175,000 miles. They cannot be solid rings, however, or they would be broken up by the

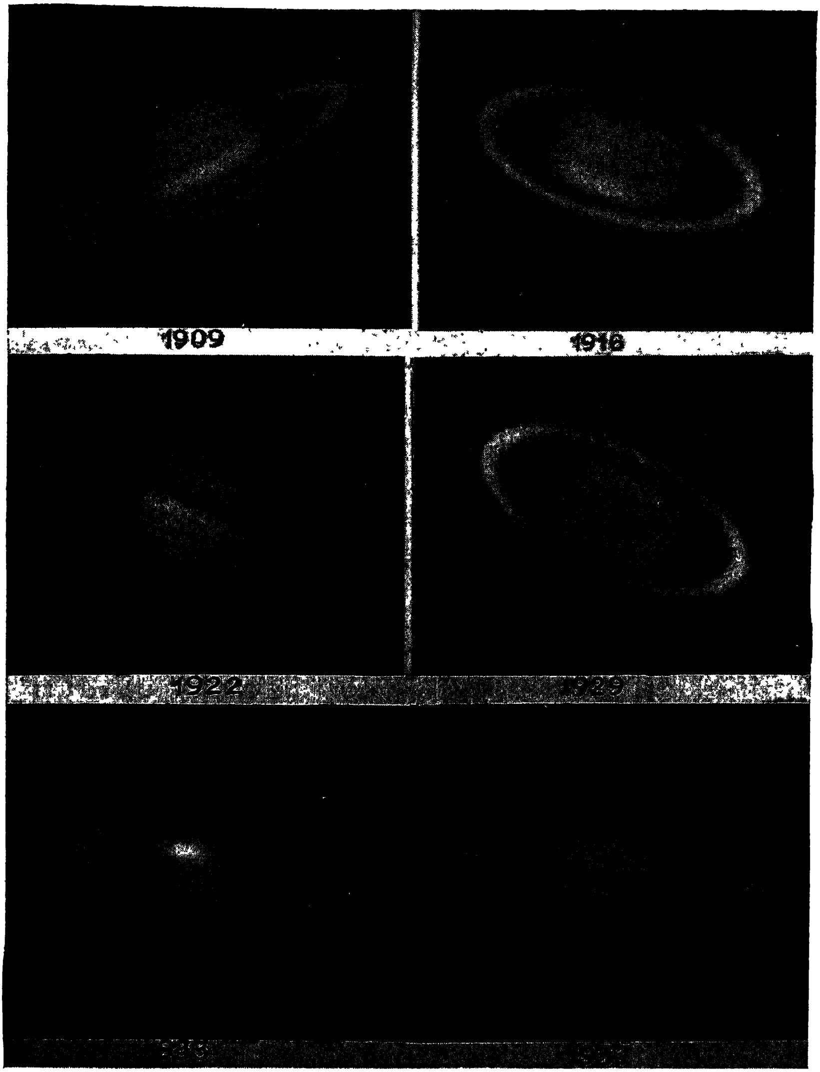


FIG. 151. Saturn. The rings appear in different phases. The White Spot is visible in the 1933 view. Photographs from Lowell Observatory

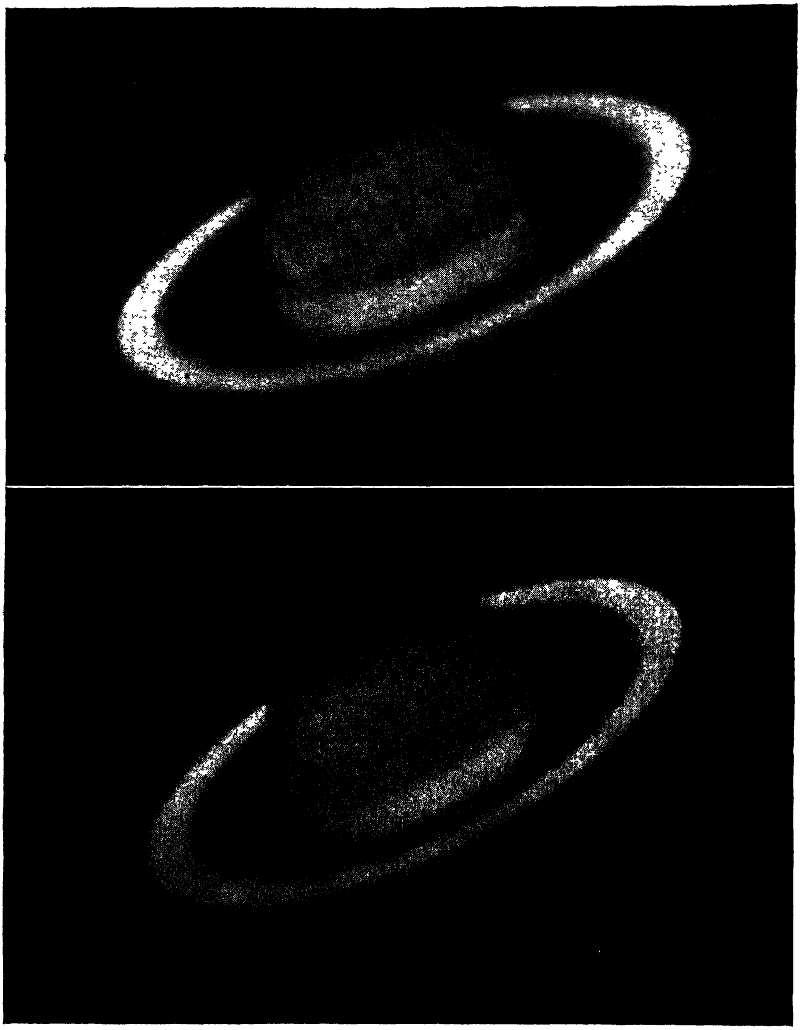


FIG. 152. Saturn. The top view was photographed in 1917, the bottom view in 1941. Note the change in the belts. Photographs from Lowell Observatory

forces of gravitation. Indeed, Saturn could not have a moon as close to its surface as the rings are, or the tidal forces, the difference in attraction for the near and far sides of the moon, would break it up. From calculations, the rings cannot be liquid or gaseous either. Spectroscopic observations show that the rings are small solid particles, like meteors.

The outer edge of the ring system goes around Saturn in 14 hours 27 minutes. The inner edge of the middle, or bright ring, goes around in 7 hours 46 minutes. Since Saturn rotates once in 10 hours 14 minutes, the outer portions go more slowly while the inner portions of the ring system go faster than the planet turns. The outer portions of the ring system rise in the east and set in the west, while the inner portions rise in the west and set in the east in the sky of Saturn.

The inner ring is the dusky, or crape, ring. It has been suggested that this ring is formed of particles which because of collisions have fallen from the outer brighter rings toward the planet. If two meteoric particles collided, their speed would be retarded so that they would fall a small distance toward the planet. The crape ring is relatively dark because these particles, which have fallen, are too few to reflect much sunlight.

The Discovered Planets

Uranus. This was the first planet to be discovered by the use of telescopes. It is sixth magnitude, barely visible to the naked eye on a good night. Sixth magnitude means about as much fainter than Alcor, as Alcor is fainter than Polaris. Such an object would not be noticed, and it is no wonder it was not found before the days of the telescope. Its diameter is 31,000 miles (see Fig. 144, page 332); its mass is fifteen times that of the Earth; its rotation period which has been determined with the aid of the spectroscope is 10 hours 45 minutes; its period of revolution is 84 years; it has four known satellites.

Uranus was found by Sir William Herschel on March 13, 1781. He thought at first that the slowly-moving object was a comet, but it soon became apparent that it was another major planet.

This planet evidently has a deep atmosphere, and is enveloped in clouds, like Jupiter and Saturn. No detail is visible in a telescope.

The orbits of the *four satellites* of Uranus are inclined almost at

right angles to the plane of the planet's orbit. They are nearly in the plane of the planet's equator, and revolve in the direction in which the planet is rotating. This is nearly perpendicular to the plane of the orbit, but it is retrograde, or backwards, rather than direct.

Neptune. The first planet discovered as the result of a prediction of its position was Neptune. It is of the eighth magnitude, quite invisible to the naked eye but bright enough to be seen with good field glasses. Its diameter is 33,000 miles (see Fig. 144, page 332); its mass is seventeen times that of the Earth; its rotation period, which has been determined with the spectroscope, is 15 hours 48 minutes; its period of revolution is 165 years; it has one known satellite.

Neptune must have a considerable atmosphere and be covered with clouds at all times. No markings can be distinguished even with the best telescopes.

Neptune's one satellite was discovered less than a month after the discovery of the planet itself. The revolution of the satellite is retrograde, or backwards, although the rotation of the planet is direct, or forwards.

The discovery of Neptune is regarded, rightly, as one of the greatest triumphs of mathematical astronomy. You have read that Uranus, the first planet to be discovered, was found in 1781. After some forty years, it was found that Uranus would not follow the orbit worked out for it by mathematical astronomers, and the existence of another planet was suspected. By 1840, the error was "intolerable," almost enough to be detected without a telescope.

Two young astronomers then began work, independently, on the problem of where another planet would have to be to pull Uranus out of its regular orbit as the observations indicated. Adams, an Englishman, finished his work first and gave his results to Airy, the director of Greenwich Observatory. Airy did not have much faith in this solution of the problem, so he asked an associate to search for the planet.

In the meantime the other astronomer, Leverrier, a Frenchman, had solved the problem and sent his results to Galle, a German astronomer. Galle went at the search seriously, and with new charts. On the very first night, September 23, 1846, he found Neptune.

When the discovery of Neptune by Galle was announced, Airy examined the observations made in England and found that the planet Neptune actually had been observed on two or three occasions. If he had taken the prediction of young Adams more seriously, the observations would have been reduced and the planet found before Leverrier had completed his work. Some British astronomers never forgave Airy for letting the credit for the discovery of Neptune get away from England.

Pluto. The most remote planet and the last to be discovered was Pluto. The discovery was the result of a careful calculation of its probable position and a thorough search. It is of the fifteenth magnitude, too faint to be seen without a large telescope. The diameter, which is uncertain, probably is about 7600 miles (see Fig. 144, page 332); the mass, also uncertain, probably is four-fifths that of the Earth; its rotation period is quite unknown, its revolution period is 248 years; there is no known satellite.

Pluto is seen as a mere point in even the largest telescopes. Consequently, neither the diameter nor the rotation period can be determined directly. Since no satellite has been found, the mass can be determined only from its effect on the motion of other planets. The method for working out the mass of Pluto was given in earlier paragraphs. From the fact that the mass of Pluto is about that of Venus, it is assumed that the diameter also is about the same as that of Venus. If this is correct, it seems that, under the best conditions, a disk might be seen and the diameter measured directly. These best conditions occur rarely, however, and to date (1942) no one has seen the disk of the planet.

The discovery of Pluto is another triumph of astronomy, similar to the discovery of Neptune. Between 1880 and 1900, astronomers found that Uranus still was not following the computed path. Neptune was so far out that it had traveled only a small part of its orbit, not enough to compute an orbit of sufficient accuracy to show the pull of a planet beyond.

Soon after 1900, the astronomer Percival Lowell began calculations on the problem. These calculations were completed in 1914, and he started a photographic search for the planet. Lowell died in 1916 without finding the planet, but he had founded an observatory which carried on the search.

In the meantime Pickering, a Harvard professor, made calcula-

tions, which he published in 1919, on the same problem. Some photographs of the region indicated by Pickering were made at Mount Wilson, but the planet was not found. Pickering's calculations were not so complete as Lowell's, and were not taken so seriously by astronomers in general.

In 1929, the Lowell Observatory renewed the search for Pluto with a new and larger photographic telescope. The new planet was found on photographs made in January, 1930. It was observed for some weeks, long enough to confirm its planetary character, and was announced March 13, 1930. March 13 was selected for the announcement because that date was the anniversary of the discovery of Uranus.

In a few months, an approximate orbit was worked out for Pluto, as the new planet was named. Then, in rechecking old plates, it was found that the Mount Wilson Observatory had photographed Pluto in 1919 in the search of the region indicated by Pickering. This showed Pickering's results were correct. Later it was found that Lowell himself had photographed it in 1914, when the methods of search were much more laborious than in 1930. The finding of these earlier observations soon after the discovery of the planet increased greatly the accuracy of the orbit.

Exercises

1. For a person in the Northern Hemisphere, when is Mercury in the best position for observation?
2. What scientific uses are made of transits of Mercury?
3. Compare the atmosphere of Venus with that of the Earth.
4. What use has been made of transits of Venus?
5. Why does the distance of Mars from the Earth vary so much? In what months can Mars come relatively close to the Earth?
6. What is known about the temperature and the atmosphere of Mars?
7. How many asteroids are known? How wide is the belt of their orbits?
8. What are the sizes of the asteroids, and what are some of the more important ones?
9. Which is the largest planet? What is its visible surface?

10. What is the probable composition of Saturn's rings? How does the density of Saturn compare with that of the other planets?
11. What is meant by retrograde motion, and what satellites have retrograde motion?
12. What was the first planet discovered after the invention of the telescope? By whom was it discovered?
13. Which was the first planet discovered by mathematical calculation? By whom were the calculations made and by whom was it seen first?
14. How was Pluto discovered?
15. What do you think of the chances for life similar to our own on other planets?

☆ XVII ☆

Comets, Meteors, and Meteorites

In addition to the Sun, Moon, planets, and stars, early people saw other objects which were more temporary. Occasionally a "fuzzy star with a tail" would appear, show in the sky for a few evenings, and then disappear. Occasionally a bright ball of fire, with a tail of fire streaming behind, would fall across the sky lighting up the landscape for a few seconds. The fuzzy star with a tail, which might show for a few evenings or even longer, was known as a comet (hairy star). The second object, the spectacular meteor, since it also had a tail, was confused with the comet by many in those days, and is confused by many even now.

In the year 1456, Halley's Comet appeared while the Turks were invading Europe. The Pope ordered prayers asking deliverance from the Turks. The story is that people added the devil and the comet also, making the prayer, "Lord save us from the devil, the Turk, and the comet." Though the return of Halley's comet in 1910 had been predicted for years, it still aroused considerable fear.

The astronomer Kepler, using the work of his master, Tycho Brahe, worked out the laws of planetary motion from which the probable positions of the planets could be predicted. For comets, however, he was not successful. Trying to predict the motion of a comet was like trying to predict the motion of a living creature, so he was half disposed to regard comets as living creatures. With one of the greatest scientists of the century feeling that way, it is no wonder that the common people of that time regarded comets with awe.

The Number of Comets. There are many more comets than the average person realizes. Including the telescopic, about five are found in an average year. The record number is thirteen, for 1932. Comets faintly visible to the naked eye, which would be seen in

that way only under the best conditions and by persons who know where to look, appear nearly every year.

Comets which can be seen as faint balls of haze and recognized as comets by the average teacher of astronomy or amateur astronomer appear every few years. In recent years such comets have appeared in 1927, 1936, 1937, 1940, and 1941; half of these would have been missed by the average teacher or amateur astronomer because of failure to learn of the comet in time, of bright moonlight, or of cloudy weather. For such a person, six comets in a lifetime would be a good record, unless he makes a special effort to find the faintest which can be seen. Spectacular comets, that is, comets bright enough to be noticed by the average individual, are much more scarce. Most persons see only one comet, and few see more than two, in a lifetime.

The Duration of Visibility. Comets have been visible for as short a time as a single evening, only one observation having been recorded. On two occasions, comets have been recorded during total eclipses of the Sun, and not before or after. For Halley's Comet, the observations at its last return extended over twenty-two months, and for a few others, the observations have extended over a longer period. For one telescopic comet, the observations extend completely around the orbit; it can be observed even at aphelion.

In the Northern Hemisphere, in general, we have the best views of comets that appear in the Spring and Summer. Comets are brightest when near the Sun; the Sun is north in those seasons, so the comets should be north when brightest. Persons in the Northern Hemisphere had an excellent view of Halley's Comet in 1910, when it was at its best in May; they had a poor view of comet 1910a, which was at its best in January.

Vanishing Comets. Many comets have been seen only once or twice at perihelion and then never seen again. Some just waste away; others have been seen to disintegrate before our very eyes. An example of this disintegration is Biela's comet, first observed in 1772. After making several routine trips around the Sun according to its calculated orbit, in January, 1846, observers were astonished to find two comets where there had been one. The return of the comet was eagerly awaited in 1852. It did reappear, but was much fainter, and has never been seen since. The general loosening up probably continued and the comet became too scattered and faint

to be visible. The disintegrating comet's connection with meteor showers will be discussed further in the section on meteors.

The Discovery of Comets. Comets are discovered in two ways: first, a search of photographs made at the observatories reveals an occasional new comet, or a known comet returning; second, sweeping the heavens visually with a telescope of low power and wide field of view reveals a considerable number. This second work is done now by amateurs with keen eyes and great familiarity with the heavens. Professional astronomers no longer search visually for comets. Some bright comets have been discovered accidentally, by

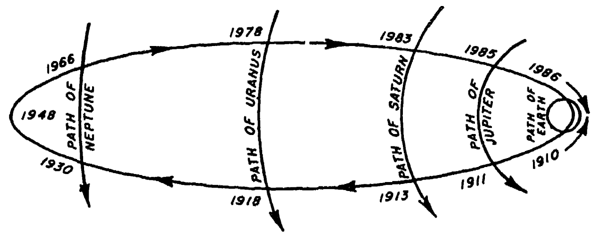


FIG. 153. The Orbit of Halley's Comet

members of the general public, and as has been mentioned, two have been found at the time of total eclipses of the Sun.

Astronomers searching, either photographically or visually, for new objects must be careful to distinguish between the small comet seen only in the telescope, and the asteroid. The essential distinction between a comet and an asteroid is that the comet shows as a relatively faint ball of light, rather than as a point of light. The asteroid, or planetoid, is a point of light, looking like a small star or planet.

Naming of Comets. Newly discovered comets are named temporarily by the year, with a small letter denoting the order of discovery. Thus, 1910a means the first comet discovered in 1910. If sufficient observations are obtained for an orbit, they are named also by the year of perihelion passage, with a Roman numeral denoting the order of perihelion passage in that year. Thus 1940 II means the second comet to pass perihelion in 1940. The more important comets are given the name of the discoverer, or of some one who has done important work on it. Peltier's Comet of 1936 is

named after L. C. Peltier of Delphos, Ohio, who discovered it. Halley's Comet, as you have read, is named after Edmund Halley, who predicted its return.

Orbits of Comets. For most comets, observations have been secured for only a few days or a few weeks out of a period probably lasting over 100 years. This is such a small part of the orbit that the observations will fit satisfactorily either an ellipse, a parabola,

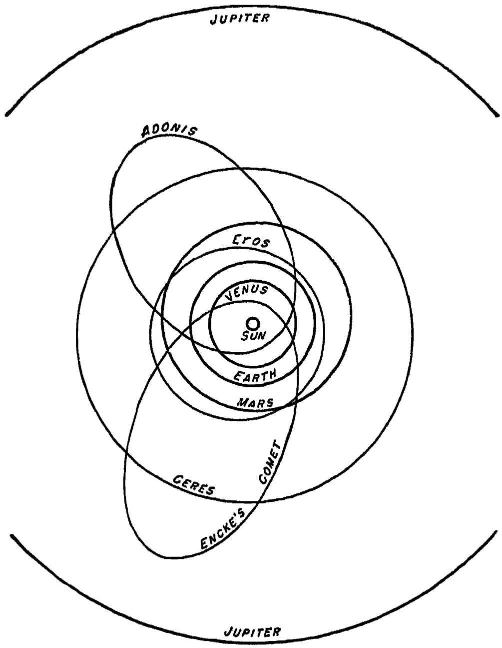


FIG. 154. The Orbit of Encke's Comet, and the Asteroids Eros and Adonis

or a hyperbola. Of the three possible orbits which fit the observations made on the average comet, the simplest is the parabola, since the eccentricity is exactly unity. (See Fig. 53, page 116.) The usual procedure, therefore, when a new comet is discovered, is to compute the orbit on the assumption of a parabola until the observations fail to fit satisfactorily. If sufficient observations are secured, the orbit is recalculated. To decide which of three possible orbits is the real orbit, astronomers must examine those for which the most observations have been secured. For these, the

FIG. 155. The Head of Halley's Comet, May 8, 1910. Photograph from Mount Wilson Observatory

orbits in all cases have been found to be elliptical. It appears, therefore, that comets are permanent members of our solar system. The orbit of Encke's Comet is shown in Fig. 154.

Some forty comets have been observed at more than one apparition. Their periods are all less than 100 years. When these comets are farthest from the Sun they are in the vicinity of Jupiter, Saturn, Uranus, and Neptune. Jupiter has a family of comets of twenty-four members. It is assumed that at one time these comets had orbits which went out far beyond Jupiter, but on one trip around the Sun they passed too close to Jupiter and were pulled by this huge planet's mass and their orbits duly shortened.

Structure of a Comet. The head of a comet is a hazy, faintly shining, ball. This head, or *coma,* is the essential part of the comet and gives it its name. Inside the coma there is usually, but not always, a *nucleus.* The nucleus is formed as the comet approaches the Sun and is seen as a starlike point near the center of the coma. Naked-eye comets always, and telescopic comets often, form a *tail* as they approach the Sun. The tail is formed by matter streaming off in a direction opposite to the Sun. Usually the tail attains its maximum length and brightness a little after the comet passes perihelion.

In volume, comets are the bulkiest members of the solar system. The head, or coma, is rarely smaller than the Earth in diameter, and for one or two comets the diameter of the head has surpassed that of the Sun. The length of the tail of a spectacular comet may be as much as one hundred million miles, or about the same as the distance of the Earth from the Sun.

The mass of any comet is exceedingly small—so little that it cannot be measured directly. Calculations from the amount of light reflected indicate that the mass of Halley's Comet, one of the most spectacular, was a little less than that of the rock and dirt removed in excavating the Panama Canal. From its mass and volume the density of the head of Halley's Comet was estimated as being equivalent to twelve small marbles per cubic mile. It is believed that the head of a comet is composed of dust and small particles surrounded by gas. The density of the tail of a comet is almost inconceivably small. For Halley's Comet the density has been calculated as equivalent to one cubic centimeter of air at sea level pressure expanded to two thousand cubic miles.

Brightness of a Comet. A comet shines by sunlight which is both

reflected by the solid particles, and absorbed and reemitted by the gas molecules. Spectroscopic observations suggest that resonance radiation is also an important factor. A radio receiving set offers an example of resonance radiation. When it is tuned to the proper wavelength, the incoming radio waves cause it to vibrate in resonance with the sending apparatus.

The tail of a comet consists of material driven from the head by the pressure of sunlight and caused to glow by the energy of the sunlight, perhaps by vibrating in resonance. As comets approach the Sun, they usually brighten rapidly but with changes in rate which make the brightness at any time hard to predict.

Recent Bright Comets. At the present time (1942), many people about seventy years of age recall a great comet of the early 1880's, and a very few of that age recall that at one time two comets were visible to the naked eye on the same night. Americans only a little younger, however, probably will recall only one comet which showed a tail visible to the naked eye. This was Halley's Comet, in 1910.

In August, 1881, for a short time two comets were visible to the naked eye, the brighter, in the evening sky, and the other in the morning sky. The comet in the evening sky showed a tail about 15° long, and the one in the morning sky showed a tail about 6° long. Even the brighter of these was lost to the naked eye in September of that year.

In September, 1882, one of the great comets of all time appeared. It was so bright that, as it rounded the Sun on September 17-18, several astronomers discovered it independently with the naked eye in broad daylight. At that time it was too close to the Sun to be seen in the night sky. As the comet moved away from the Sun, it came into the morning sky where it was a brilliant object in October and November of that year, with a tail between 20° and 25° long. No later comet has been so brilliant, but Halley's Comet showed a longer tail.

Following the great comet of 1882, no comet with a really noticeable tail was visible to those living in the United States until January, 1910. The comet known as 1910a appeared in January, 1910. This was a brilliant comet for the Southern Hemisphere, but few in the United States saw it.

Halley's Comet became visible to the naked eye in April, 1910, and in early May was a magnificent object in the morning sky. This most famous of comets will be discussed more fully later.

In the next year, 1911, another bright comet appeared. This comet, Brooks', was a fine object in the morning sky for a short

FIG. 156. Halley's Comet and Venus rising over Flagstaff, Arizona, May 13, 1910. The tail is disintegrating on the lower side. Photograph from Lowell Observatory

time in October. Seven or eight degrees of tail could be seen easily with the naked eye. Because of the hour at which it appeared, and because it was not predicted, few, excepting astronomers, saw it. Since 1911, no comet with a tail visible to the naked eye, or bright enough to be noticed by the average person, has been in good position for viewing from the United States. No one knows when the next bright comet will appear, but astronomers hope sev-

eral such will be visible before 1986, the next return of Halley's Comet.

Halley's Comet. Halley's Comet is the first comet whose return was predicted, and it is the only bright comet whose period is short enough for its return to be predicted with reasonable accuracy. Edmund Halley, after whom the comet is named, was a friend of Sir Isaac Newton, and one of the early directors of the Greenwich Observatory. When calculating the orbit of a bright comet appearing in 1682, he found the orbit to be nearly identical with those of comets of 1607 and 1531. From further study, he became convinced that these were reappearances of the same comet and ventured to predict its return in 1758 or 1759. The comet did return in 1759, and also in 1835 and 1910.

From the more complete and accurate observations at later returns, the orbit has been determined accurately as shown in Fig. 153, and records of earlier appearances have been identified. The comet has been recorded at every appearance from 87 B.C. to 1910 inclusive. There is no record of the return in 163 B.C., but there is a record of a comet, probably Halley's, in May of 240 B.C. The records examined are from Europe, China, and Japan, one appearance, 912 A.D., being recorded only in Japan. One of the interesting appearances is that of April, 1066, at which time Halley's Comet attracted the attention of all Europe. In England, it was assumed that the baneful influence of this comet was responsible for the death of King Harold and the success of the Norman invasion. Another interesting appearance was that of 1456, referred to in an earlier paragraph.

At its latest return, astronomers began photographing the region where it was expected as early as 1908, but it was found first on a photograph made September 11, 1909. After the announcement, it was found on a few earlier photographs, the earliest having been taken at the Helwan Observatory in Egypt on August 24 of that year. The comet was observed with the naked eye on April 19, 1910, at the U. S. Naval Observatory, and by a considerable number of astronomers, both professional and amateur, on the morning of the following day. As seen with the naked eye these first mornings, the comet appeared as a faint ball of haze, visible for only a few minutes. Ten minutes after it was high enough above

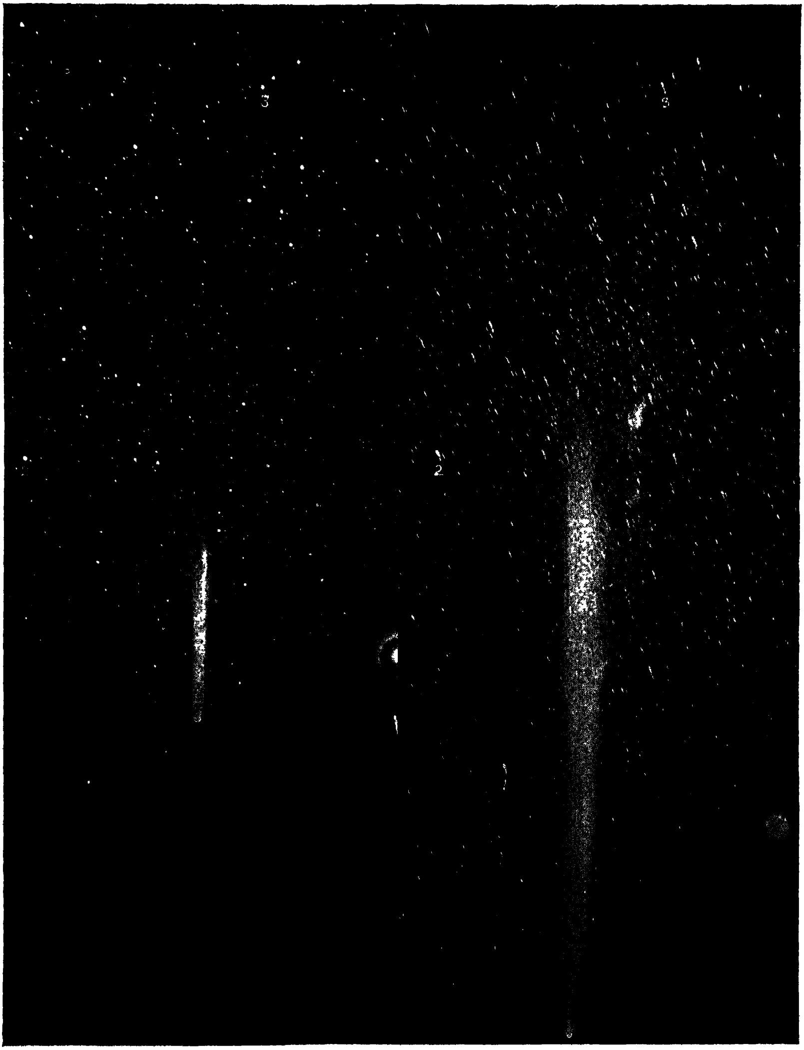


FIG. 157. Halley's Comet on May 4, 1910 (left), and May 13, 1910 (right). Photographs from Lowell Observatory

the horizon to be seen, approaching dawn made it invisible to the naked eye.

On April 25, the tail was little more than a quarter of a degree long, or half the distance across the Moon. By May 4, it was nearly 5° long, almost long enough to reach from one pointer star of the Big Dipper to another, and bright enough to attract the attention of anyone outdoors. The left photograph in Fig. 157 shows the ap-

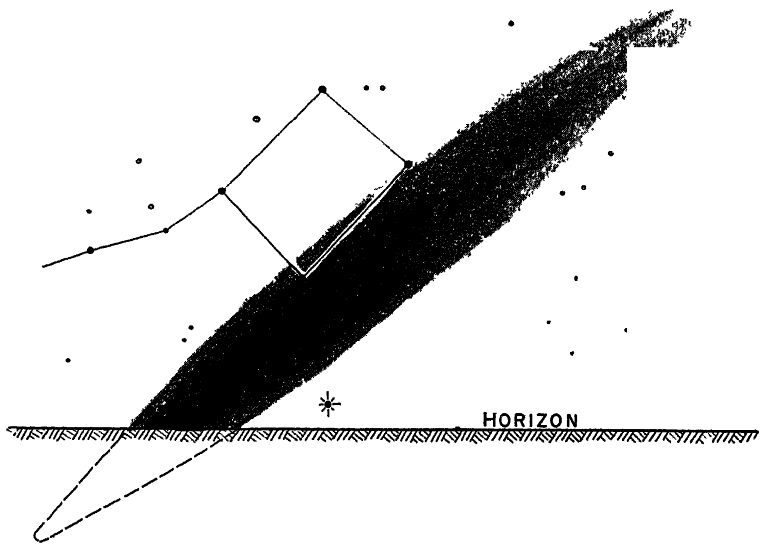


FIG. 158. The Tail of Halley's Comet May 18, 1910, 3:15 a.m.

pearance on that morning. On the morning of May 14, the length of tail visible was 39°, or long enough to reach from an average good horizon to the North Star in latitude 40°. By May 18, the head of the comet was so close to the Sun that it did not rise until well after dawn. Before dawn, however, the tail of the comet stretching across the southeastern sky was a magnificent spectacle. Some 90° of tail could be seen, appearing about as bright as the Milky Way on a clear, moonless night. A drawing by the author (Fig. 158) shows the appearance on the morning of May 18.

Calculations indicate that the Earth passed through at least the

outer portions of the tail of Halley's Comet. It is interesting that, as the Earth approached and passed through the tail, the head of the comet could be seen in the evening sky and the tail in the morning sky on the same day. On May 19, the tail of the comet was in the morning sky, nearly as conspicuous as on the preceding morning. On that evening, the head of the comet, without any tail, appeared in the west after sunset. On the morning of May 20, some of the comet's tail could be seen in the eastern sky. On that evening, the head of the comet, with some tail, could be seen in the western sky. On the morning of May 21, the tail had disappeared from the eastern sky.

As the comet came into the evening sky, it was moving farther from the Sun, having passed perihelion (closest to Sun) on April 19. Hence, it was getting fainter. There was a nearly full Moon in the evening sky. The light of the Moon, added to the real decrease in brightness of the comet, made it a much less conspicuous object in the evening sky than it had been in the morning sky. On May 25, the tail was about 20° long. By June 4, it had decreased to less than 10° long, and was much less conspicuous. The last recorded naked eye observation is that of Curtis, at the Lick Observatory, on June 28, 1910. With telescopes it was followed a year longer, or until June, 1911, when it had passed beyond the orbit of Jupiter.

The comet reached the orbit of Neptune about 1930, and will reach aphelion (farthest from the Sun) about 1948. Probably it will be found again by astronomers sometime in 1985. An accurate calculation of its return has not been made yet, but it should reach perihelion about April, 1986.

Meteors

On any clear night when the Moon is not shining, a watcher of the sky will see occasionally a "star" dart a short distance across the sky, and disappear. This is not a real star, but a meteor.

In beginning the study of meteors, it is helpful to define the various words associated with them. First, *meteor* refers to a small particle of material which enters our atmosphere and is made luminous by the friction of the air. The term meteor refers to the object only while it is luminous. The term *meteoroid* applies to the particle traveling in outer space before it has reached our

atmosphere. *Meteorite* refers to a complete piece of stone or iron dropped by a meteor. The three terms are related as words tree, trunk, and board, meteor corresponding to tree, meteoroid to trunk, and meteorite to board.

Meteors are designated by three descriptive terms. A shooting star is a meteor not brighter than the planet Venus. A fireball is a meteor brighter than the planet Venus. A detonating meteor is one from which thunder-like or explosion-like sounds are heard.

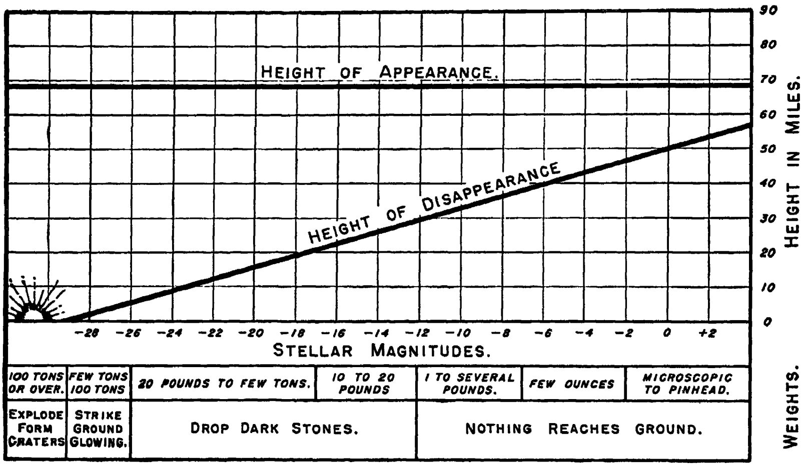


FIG. 159. The Height of Appearance and Disappearance of Meteors according to Size

Heights of Appearance and Disappearance. Small meteors appear at altitudes of about 68 miles and disappear at altitudes of 54 miles. Fireballs also appear at a height of about 68 miles, but the height of disappearance varies with the brightness or mass of the meteor. A meteor about as bright as the full Moon bursts and disappears at a height of 20 to 25 miles. If it is dropping meteorites, it comes even lower. The Paragould meteorite continued to glow until about five miles from the ground. (See Fig. 159.)

In general, the smaller meteors, from microscopic ones seen only in the telescope up to those weighing about 10 pounds and having a brightness equal to the full Moon, are completely consumed in the atmosphere. Those as bright as the full Moon may come as low as 20 miles, or thereabouts, before bursting; but in general, nothing larger than dust particles reaches the surface of the Earth.

Meteors weighing between 10 pounds and a few tons drive through the atmosphere to heights varying from a fraction of a mile to 20 miles, at which heights they burst. If the original velocity is low enough, some of the pieces after bursting have their velocity reduced quickly to a point where they do not glow, and the surviving fragments drop to the surface of the Earth as dark stones or meteorites.

The Number of Meteors. The number of meteors observed on a clear night by a single person is about ten per hour. Special observations have shown that a single person can cover an area of about 2000 square miles, or 1/100,000 the total area of the World. This means that for the World as a whole about 1,000,000 meteors per hour, or 24 million per day, bright enough to attract the attention of the observer, must fall.

This number is of little value, however, unless the limiting magnitude is known. A number of special observations have been made, chiefly at Iowa and Harvard, with the estimated magnitude and distance of the meteor from the center of the field recorded. From this work it has been calculated that the 24 million per day included fourth-magnitude meteors. A series of observations was made at Iowa, at Princeton, and at Harvard, and all agree closely on the increase of the number of meteors with fainter magnitudes and indicate that the number of telescopic meteors reaches millions of millions at about the 15th magnitude.

Meteor Showers. In November, 1833, startled Americans saw meteors fall as thick as snow flakes, as many as 20 per second. A meteor shower is such a fall, and all of the paths of members of such showers radiate from a single point in the sky known as the *radiant.* The shower is named according to the place of the radiant, and thus we have the Leonids, Andromedes, Perseids, and Lyrids.

These meteor showers are connected with cometary orbits. Schiaparelli showed that the August, or Perseid, meteors are moving in the same orbit as Tuttle's Comet. Subsequently, the discovery was made that the Leonids (see Fig. 160 and Fig. 164) have the same path as Tempel's Comet of 1866. The Andromedes follow in the track of Biela's Comet; the Aquarids are connected with Halley's Comet, and the Taurid meteors with Encke's Comet.

How are these meteor streams formed from the parent comet? At first they are close to, or part of the parent. Then as planetary

perturbations gradually influence them, they stray away, either ahead of or behind the parent, but still in the same orbit. After a sufficiently long period of time they may be distributed uniformly along the orbit.

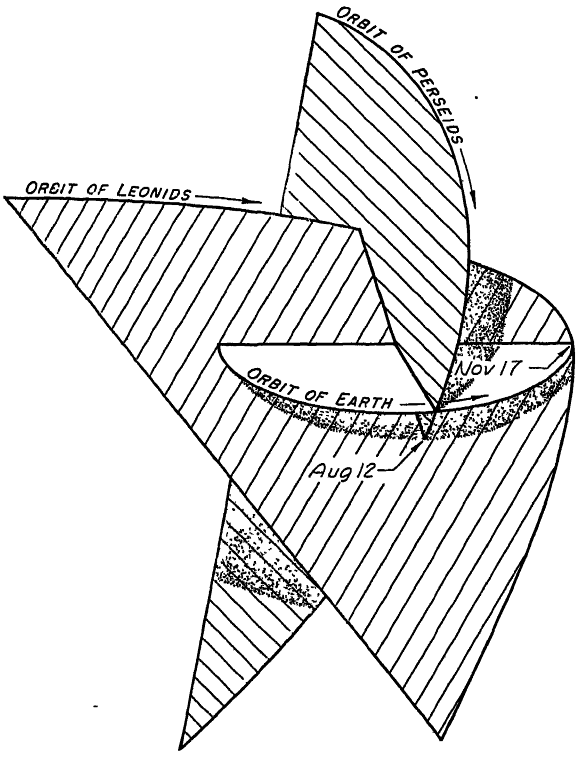


FIG. 160. The Orbits of the Earth, the Perseid Meteors, and the Leonid Meteors

The Masses of Meteors. A shooting star which appears about as bright as the North Star must be somewhat smaller than a large pin head. Telescopic meteors grade down in size to particles so small that they are driven by the pressure of light. A meteor as bright as the full Moon probably weighs seven or eight pounds. Meteors dropping meteorites are larger. The largest which have been observed in recent years probably weighed about one ton before bursting.

Distinguishing Meteors from Comets. Because the general public often calls a bright meteor a comet, it is well to bring the more important distinctions together into one paragraph, as follows: The *light* of the comet is about that of a star, while the light of the spectacular meteor is about that of the Moon. The comet is *visible* for days or even months, while the meteor is visible for only a few seconds. The comet seems to remain *stationary* among the stars, while the meteor sweeps rapidly across the sky. The comet is a swarm of small and widely scattered particles, while the meteor is a single solid particle. The *volume* of the comet is greater than that of the Earth, while the meteor is no bigger than an ordinary ten-pound stone. The comet is millions of miles away, while the meteor is usually less than two hundred miles away, and always in the Earth's atmosphere.

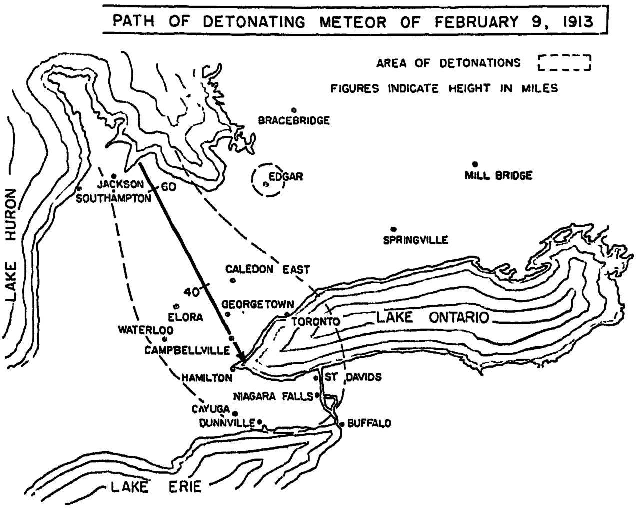


Fig. 161. The Path of the Detonating Meteor of February 9, 1913

Meteorites

As meteorites are the only visitors that actually come in to us from outer space, they are of special interest. In general, astronomers have only the light of the heavenly bodies from which to

obtain information, but meteorites are tangible samples which can be studied in the laboratory.

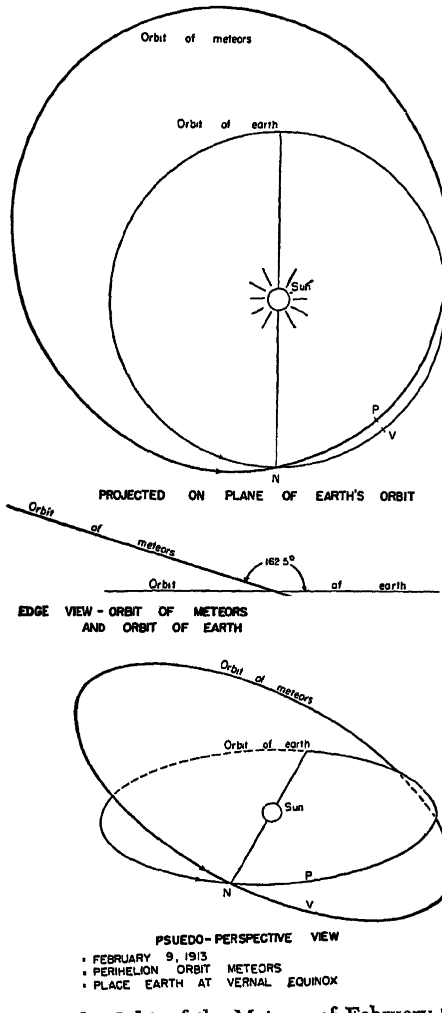


FIG. 162. The Orbit of the Meteors of February 9, 1913

The Number of Meteorites. The approximate number of meteorites reaching the Earth can be calculated from the number that fall close enough to farmers and farm laborers to attract attention.

Using the records of meteorites recovered and census statistics on the number of farmers and farm laborers, it appears that the annual number of meteorites falling in the United States must be 150-170 per year. The total number falling in the whole World must be about 11,000 per year.

Only a small fraction of the total number are recovered. This is what would be expected by anyone who has given the matter thought. If it appears that a meteorite weighing about nine pounds has fallen in a certain region, the point of fall normally is uncertain by two or three miles. The area which should be searched to find it is about 25 square miles. Imagine the time required to search this thoroughly enough to find a partially buried stone, which appears little different from other stones. The difficulty is indicated by the fact that the hole made by the 800-pound Paragould stone, although more than eight feet deep, and within a quarter of a mile of a farm house, was not found until 27 days after the fall.

How Meteorites Are Found. A high percentage of stone meteorites are found because they are actually seen to strike as dark stones; or dust, water, or snow is seen to fly, by persons who hear the stone falling and are watching for it. Others are found because persons who hear the thud of striking from various directions search, and come together quite close to where the meteorite actually struck.

Most iron meteorites have been found by farmers while plowing, and the date of fall is not known. A piece of iron will be picked up as strange long after falling, while an old stone plowed up will not be considered unusual.

The Rate of Fall of Meteoric Material. From the number of meteors of each magnitude, and the calculated mass of an average meteor of each magnitude, a curve can be constructed showing the total mass of material which reaches the Earth from meteors of each magnitude. Although the number of meteors approaches infinity as smaller magnitudes are approached, the total mass does not. The total mass including on the one hand the very largest meteors, such as those which form meteor craters, and on the other hand, the very smallest telescopic meteors, can be calculated approximately. It appears that, at the present rate of fall, the layer of meteoric material formed on the Earth would be less than an inch thick in twenty billion years.

The Temperature of Meteorites. There are two common misbeliefs about the temperature of meteorites. The first is that a freshly fallen meteorite should be exceedingly hot, hot enough to set fire to things. The second is that the meteorite (technically the meteoroid) is at a temperature not far from absolute zero when it enters the Earth's atmosphere.

Calculation shows that a meteoroid at the Earth's distance from the Sun should be at a temperature not far from freezing. The Sun's rays shining on it will raise it to about that temperature. When this meteoroid, at a temperature not far from freezing, reaches the Earth's atmosphere, the molecules of air strike it at high speed, knocking molecules from the meteoroid. These molecules stream off, glowing brilliantly, like sparks from an iron held against an emery wheel. However, the passage to the point where the meteor bursts and ceases to shine requires only a few seconds and only a thin surface layer is heated. After bursting at a height of five to fifteen miles, the velocity of small pieces is quickly reduced to a point where they do not shine, and these pieces, or meteorites, drop as dark stones through the lower part of our atmosphere.

The observed temperature of meteorites picked up immediately after striking the ground agrees with what we would expect from these considerations. The coolest have been so cold that when the meteorite was dug out of the ground, crystals of ice and frost were sticking to it. The warmest have felt rather hot, but in no case has a meteorite been too hot to handle when picked up immediately. In other words, the observed temperatures vary from a little below freezing to somewhat warmer than "milk warm."

Composition and Appearance of Meteorites. Meteorites are of two varieties, the stony ones which are the most numerous, and the metallic ones. The stony meteorites contain a high percentage of oxides of silicon and magnesium, being higher in magnesium than terrestrial rocks. They almost always include particles of metallic nickel-iron scattered throughout the stone. A thin surface layer is melted into a dark glassy coating. A typical stony meteorite resembles a mass of cement which has been molded by hand, leaving finger prints, then painted a glossy black.

The metallic meteorites are composed chiefly of nickel-iron, with

a surface layer altered by heat. If cut, polished, and etched with acid, the metallic meteorites shows a different pattern from man-made iron and steel. The "Widmanstätten figures" are the best test as to whether a piece of metal is of meteoric origin.

The great majority of "dated" meteorites, that is, meteorites for which the date of fall is known, are stony, but the majority in

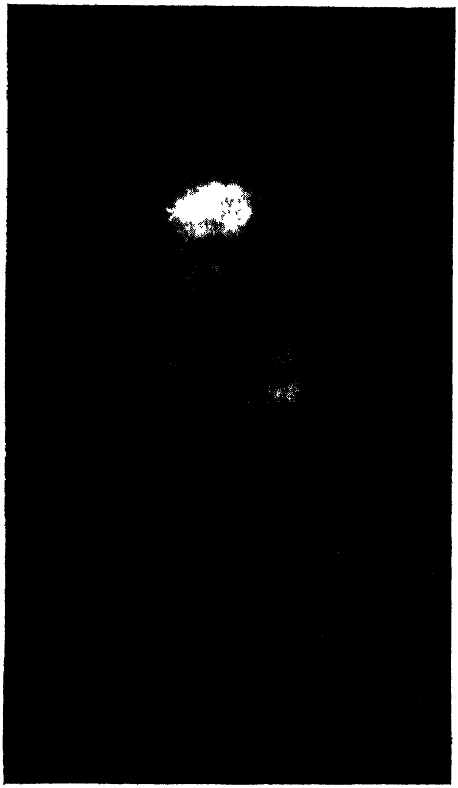


FIG. 163. Smoke Cloud from the Detonating Meteor of March 24, 1933. Photograph from O. E. Monnig

museums are of iron. This is due to the fact that in most regions, a stony meteorite would be missed unless picked up very soon after its fall, while a metal meteorite will attract attention even if found centuries after its fall.

Sounds from Meteors. If a meteor is large enough to come relatively low, that is, if the bursting point is at a height of 20 miles or lower, the following sounds may be reported.

Persons near the point of fall report a *sharp detonation,* or series of detonations followed by a *rumble like thunder* rolling back into the distance. A time interval, usually of a minute or more, elapses between the appearance of the meteor and the hearing of the first detonation. This, of course, is what would be expected by persons

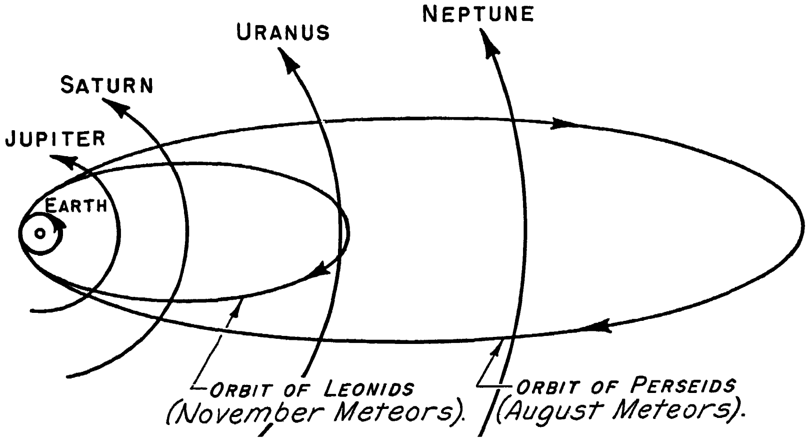


FIG. 164. The Orbits of the November and August Meteors

who have seen lightning and then heard the thunder several seconds later. The time elapsed is the interval required for the sound wave to come from the meteor to the observer's ear.

1. *The detonation,* or sharp clap like thunder, is heard when the shock wave, similar to the compression which moves outward from the point of an explosion, reaches the observer's ear.
2. After the wave of compression passes the observer, there normally are numerous echoes from buildings and hills. These echoes give the effect of a *rumble rolling* off into the distance and in the direction from which the meteor came.

3. Persons near enough to hear the actual fall of meteorites call the sound a *hum* similar to the sound of an airplane.
4. Letters from persons who have observed brilliant meteors practically always include some letters reporting a fourth type of sound. This is a swishing or hissing similar to the "sound of a sky rocket" and is reported as heard simultaneously with the appearance of the meteor. However, this sound is in no way connected with the meteor. It seems generally to have

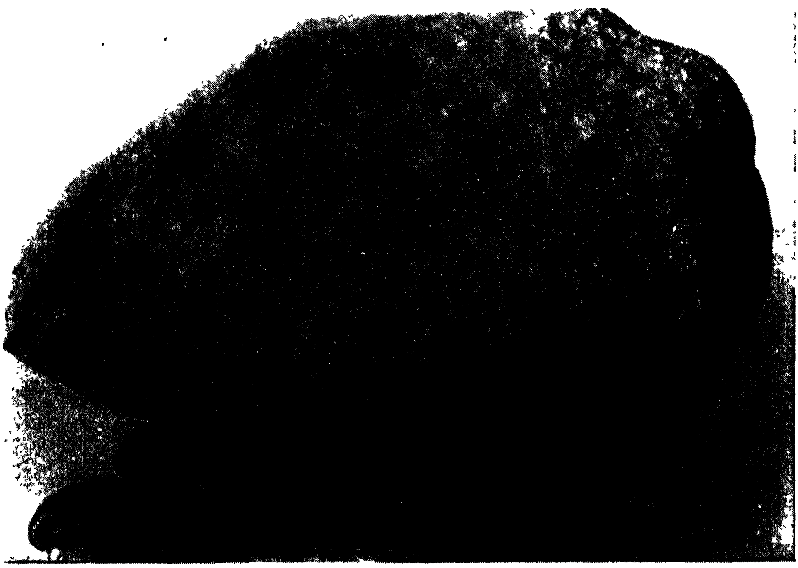


FIG. 165. The Paragould Meteorite

been some extraneous noise or the result of overimaginative reporting.

Orbits of Meteors. As you have read in the paragraphs on meteoric showers, many of the shower meteors are moving in the orbits of comets. Hence the orbits of these meteors have large eccentricities, between nine-tenths and unity, and large inclinations, in some cases more than 90°, so that the motion is retrograde, or opposite in direction to the motion of the Earth and planets. Perhaps many of the other shooting stars were moving in such orbits before falling into

the Earth's atmosphere. Fig. 160 and Fig. 164 show the orbits of the Perseids and Leonids.

The spectacular meteors, in general, were moving in different orbits. Calculation shows that these shadow casting objects, which produce detonations and occasionally drop meteorites, were moving in orbits of much smaller eccentricity and inclination. These meteors were moving in direct orbits of relatively short period,

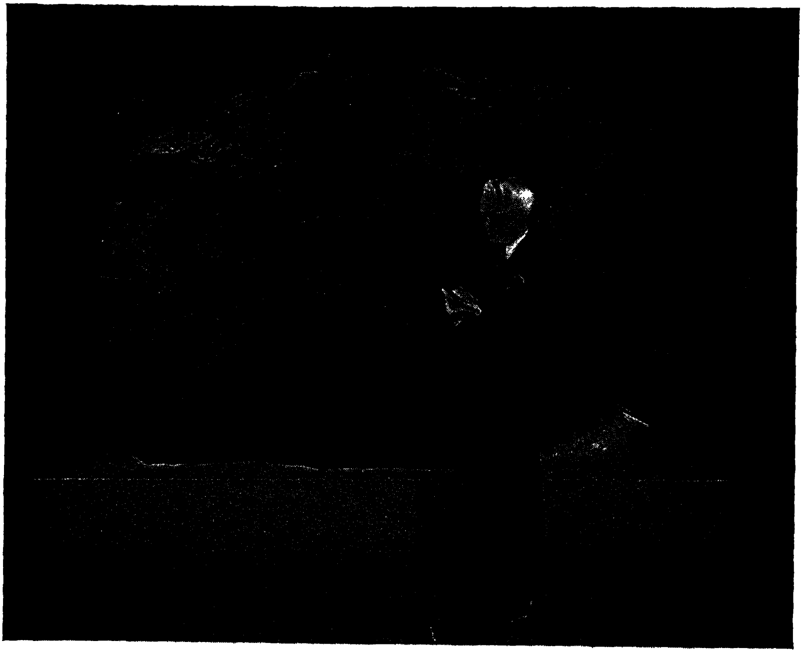


FIG. 166. The Cape York (Ahnighito) Meteorite. Photograph from American Museum of Natural History

similar to that of the asteroids. Presumably, therefore, the shooting stars are related to the comets, and the spectacular meteors are related to the asteroids.

Record Meteorites. A meteorite belongs to the owner of the land upon which it falls. Museums and collectors then buy the meteorites for exhibition. The following list gives some of the largest meteorites, interesting facts about them, and where they are located.

1. The largest meteorite for which the *date of fall* is known is

the *Paragould, Arkansas,* which fell Feb. 17, 1930. Weight, 800 pounds. Depth of hole, 8 ft. ¾ in. It is a stone meteorite and is now in the Field Museum, Chicago, Illinois. This is also the largest *stone* meteorite *not broken at time of fall.*

2. The *largest stone* meteorite. *Long Island, Kansas.* Weight, 1300 pounds. Date of fall unknown. Now in Field Museum, Chicago.
3. The largest meteorite in any museum. The *Cape York, Greenland* meteorite. Weight, 36½ tons, *iron.* Brought by Robert E. Peary to American Museum of Natural History, New York City. Must have fallen in prehistoric times.

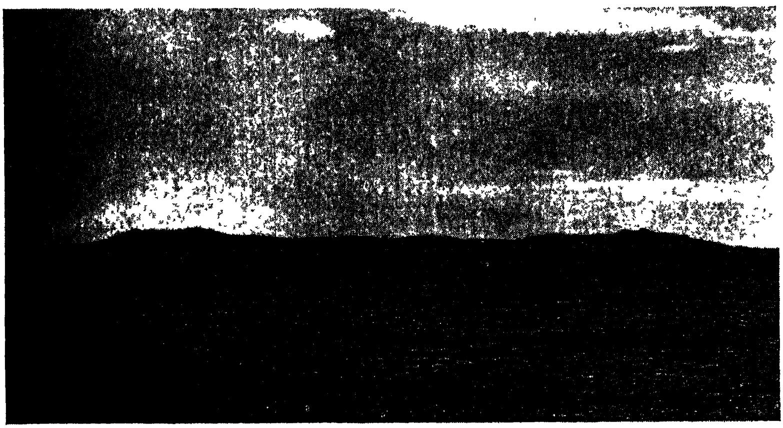


Fig. 167. Meteor Crater, Showing the Rim Rising 150 Feet above the Surrounding Plain. Photograph by Clyde Fisher

4. The largest meteorite recovered in America. The *Willamette, Oregon.* Weight, 15 tons, *iron.* Evidently brought to place of finding by glacier during the ice period. Now in the American Museum of Natural History, New York City.
5. The largest meteorite known. The *Grootfontein, South Africa.* Weight, 50-70 tons, *iron.* Date of fall unknown. Still lies where it was found.
6. Oldest meteorite on record. *Ensisheim, Alsace.* Fell in 1492, when Alsace was part of Germany. Was placed in a church near where it fell at that time. Almost the whole of the original meteorite is still there.

Meteoric Craters. Meteors from a few tons in weight and up would, in general, reach the ground while still shining. That is, they would reach the ground as meteors traveling at a velocity of several miles per second. The minimum speed with which a meteor can enter the Earth's atmosphere is 6.95 miles per second. Calculation indicates that a meteor 100 tons in weight, unless entering at a low angle, would strike the ground at a velocity of 2.3 miles per second or more; which would mean an explosion equal to that of

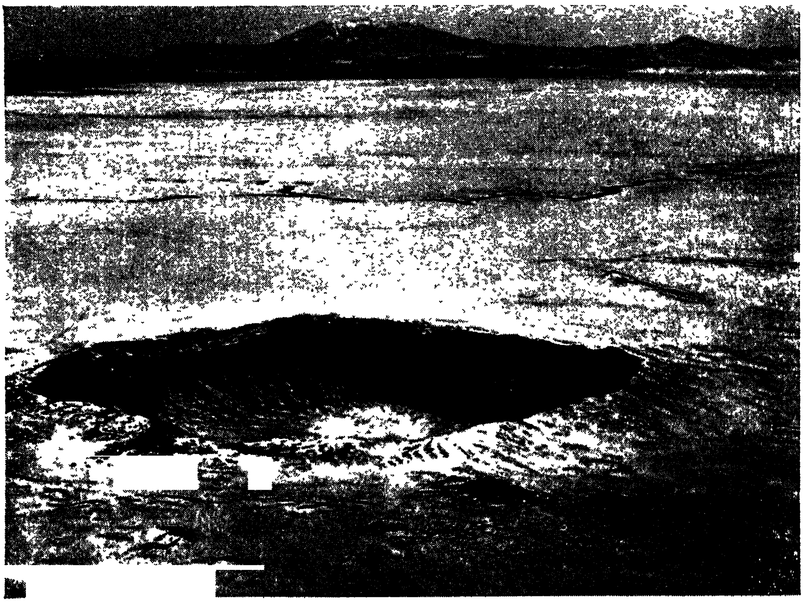


FIG. 168. An Aerial View of Meteor Crater. Photograph from American Museum of Natural History

its own weight of nitroglycerin. It appears to be impossible for anything larger than 50 or 60 tons to reach the surface of the Earth at a velocity low enough to survive unbroken, and it is certain that a much larger meteor would strike the ground with a velocity such that it would vaporize and explode.

These large meteors, which explode on striking, produce meteoric craters. The first such crater identified was Meteor Crater, near Winslow, Arizona. A meteor, probably between thirty and sixty feet in diameter struck in prehistoric times. Because of its mass, it

struck with a velocity such that nearly all of the meteor, and much of the rock with which it came in contact, was vaporized. This sudden vaporization was equivalent to the explosion of 200,000 tons of nitroglycerin.

The explosion produced a crater 4150 feet in diameter, and 600 feet deep, with the rim raised 150 feet above the surrounding plain. Several tons of meteoric iron have been picked up in the vicinity.

There is a smaller crater near Odessa, Texas, from the rim of which considerable meteoric iron has been recovered, and meteoric craters have been found in Australia, Arabia, and elsewhere.

The only meteoric craters produced in historic times are those in central Siberia, from a huge meteor which fell June 30, 1908. This meteor probably weighed 200 to 300 tons, and may have been 12 to 15 feet in diameter before striking. The region was not investigated until after a lapse of twenty years, and the available information is far short of what scientists would like. It appears that there was devastation over a region of 30 miles in diameter, but this obviously was a much smaller meteor than those which produced the prehistoric craters.

Exercises

1. About how many telescopic, naked-eye, and spectacular comets appear each year?
2. When is the best time of the year for viewing comets in the Northern Hemisphere?
3. What is the explanation for the disappearance of comets?
4. How are comets discovered?
5. How are comets named?
6. What shape is a comet's orbit?
7. What is the structure of a comet? What are the sizes and densities of the various parts? choose 1 particular comet.
8. If a comet appears to move 10° in one day and is 24,000,000 miles from us, how fast is it traveling?
9. If a comet's head is globular, 20,000 miles in diameter, and 500,000,000 tons in mass, what is its density?
10. What causes a comet to be luminous?
11. Name the bright comets of the last 70 years.

12. What is the period of Halley's Comet? Why is this comet of such interest, and what is the date of its next return?
13. Explain the terms meteor, meteorite, and meteoroid.
14. Into what three classes are meteors divided according to size and brightness?
15. What are the heights of appearance and disappearance for meteors in size about a grain of dust, 10 pounds, 50 pounds, 100 tons? (See Fig. 159.)
16. How many meteors fall per day on the Earth, including those of magnitude 4? those of magnitude 15?
17. What connection is there between metor showers and comets?
18. What are some of the important differences between comets and spectacular meteors?
19. How many meteorites fall on the Earth each year?
20. What is the approximate ratio between the number of meteors striking the atmosphere and the number of meteorites which reach the ground each year?
21. What is the temperature of freshly fallen meteorites? What is the temperature of a meteoroid in outer space?
22. Of what materials are meteorites composed? How can they be distinguished from ordinary stones and rocks?
23. What sounds accompany the fall of a meteorite?
24. What type of orbit do meteors have? Are their orbits similar to those of any other members of the solar system?
25. What is the largest meteorite known? the largest in any museum?
26. What is the probable size of the meteor which formed Meteor Crater?
27. Where are some other craters known to have been formed by falling meteors?

☆ XVIII ☆

The Sun

Even early people knew that the Sun was necessary for life. They could observe that as the Sun moved higher in the sky, and was shining for more hours each day, the weather was warmer, and that as the Sun moved lower in the sky and the hours of daylight became shorter, the weather became colder. (See Fig. 59, page 126.) Plant life, and to some extent, animal life, would develop in the Spring, flourish in the Summer, and in many cases become dormant, or die, as Winter approached.

It was quite natural for these early people to worship the Sun as a god. Temples were built to it in all parts of the world. A common symbol of the Sun, found in these early temples, is a winged wheel, or disk. It is assumed that this is a representation of the appearance of the Sun in an eclipse near sunspot minimum, when the corona gives the effect of a pair of wings for the black disk of the Moon.

The Size of the Sun. The apparent size of the Sun is almost exactly the same as the apparent size of the Moon, as you have read, although the distance of the Sun is about 400 times as great as the distance of the Moon. This apparent diameter is just about half a degree ($\frac{1}{2}°$), or it is the apparent diameter of a disk one foot in diameter at a distance 110 feet from the eye.

The modern figures for the size and distance of the Sun are: diameter, 864,000 miles, and distance, 93,000,000 miles. The volume is 1,300,000 times that of the Earth. In Fig. 144, page 332, the sizes of the nine planets as compared to a section of the Sun are shown. The mass is 332,000 times that of the Earth. The surface gravity is nearly 28 times that at the surface of the Earth.

As the Sun is gaseous throughout, it does not rotate as a solid. The *rotation period* of the Sun at its equator is 25 days, and near

the poles, about 34 days. These are the sidereal, or true, periods. The synodic period, because of the movement of the Earth in its orbit, is longer, being 27 days for the equator. The rotation can be determined from sunspots, or by the Doppler principle, which will be explained later in this chapter.

The Layers of the Sun. The sun is gaseous throughout, as you have read, and from calculations made according to modern physics,

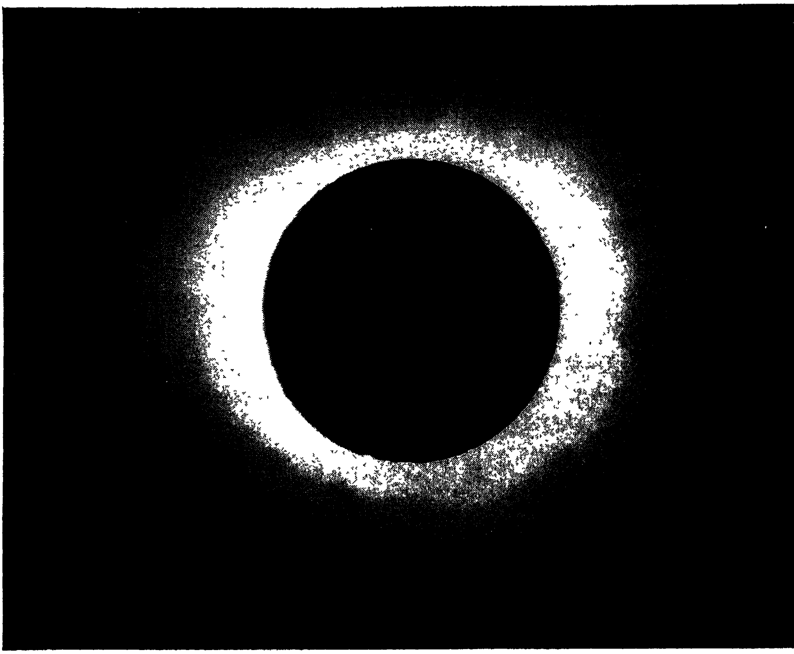


FIG. 169. The Solar Corona, June 8, 1918. Photograph from Yerkes Observatory and University of Chicago Press

the temperature of the interior must be millions of degrees centigrade. This hot interior is called the *nucleus*.

In the visible surface of the Sun the density and the temperature become low enough for the material to shine as a transparent rarefied gas rather than as an opaque compressed gas. This visible surface is called the *photosphere*. Calculation indicates that the density at the surface of the photosphere is only a fraction of that of air at sea level. This is less than one would expect, but at the

temperature of the surface of the Sun a glass tube of ordinary air would shine as an opaque solid rod.

Just above the photosphere the gases of the Sun become rare enough and cool enough to be transparent, yet they are hot enough to shine. This layer which can be seen at the time of an eclipse of the Sun, is called the *reversing layer*, and it is the bottom part of the *chromosphere*; in other words, the chromosphere includes the reversing layer. The upper part of the chromosphere includes the reddish prominences looking like tongues of flame, best seen at the time of a total eclipse.

At the time of an eclipse of the Sun, streamers of a pearly gray light can be seen extending out from the black disk of the Moon, often as far as several times the Sun's diameter. This pearly gray halo surrounding the eclipsed Sun is called the *corona.* The corona may be considered the outer and more rarefied atmosphere of the Sun.

The photosphere, or visible surface of the Sun, is composed of gases which are less dense than air at sea level pressure. As seen in the telescope, it is mottled in appearance, decidedly uneven.

The most conspicuous features in the photosphere are the sunspots, relatively dark and nearly circular markings. These spots are really storms on the Sun, resembling tornadoes on the Earth. The darker center of the spot is called the *umbra,* and the surrounding lighter portion is called the *penumbra.* Normally the lines of demarcation between umbra and penumbra, and between penumbra and the surrounding photosphere are definite.

In size, the spots range from small ones, barely visible with modern equipment, to ones 50,000 or 60,000 miles across. Such a spot is visible to the naked eye through thin clouds, or through film or glass dark enough to protect the eye. The duration of sunspots ranges from a few hours for the smallest to more than a year for some of extraordinary disturbance.

The Sunspot Cycle. The number and size of the spots on the Sun increases and then decreases in a period of about 11 years. The interval from a time of many and large spots to the next time of many and large spots averages about 11.13 years. Closer observation, however, shows that successive sunspot maxima are not the same, but that alternate maxima are higher. For example, there

were more and larger spots in 1917 and 1918 than in 1927 and 1928. At the next maximum, 1937 and 1938, there were more and

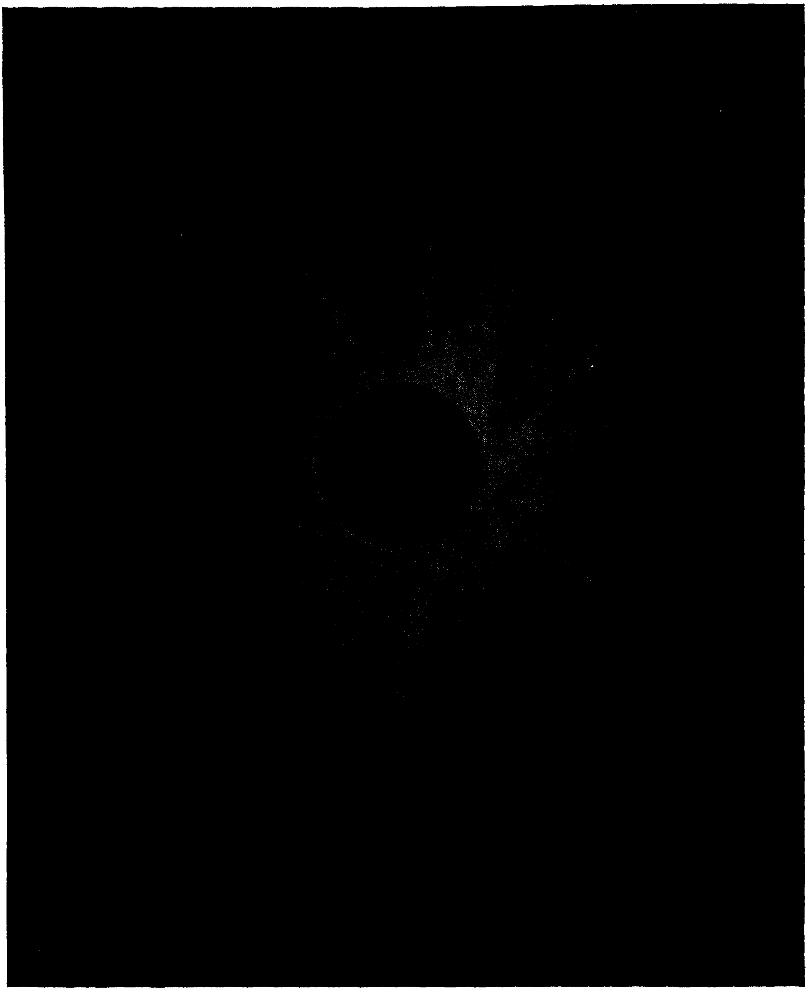


FIG. 170. The Corona near Sunspot Maximum. Drawn by H. R. Morgan of U. S. Naval Observatory

larger spots again. It has been found also that the magnetic polarity of the spots changes in alternate maxima. The real period, therefore, for the sunspot cycle is 22.2 years.

The spots can be used for measuring the rotation of the Sun. An average spot goes all the way around and comes back to the center of the sun's disk in about 28 days.

Terrestrial Effects. The solar variations in the eleven (or twenty-two) year cycle are responsible for small terrestrial variations. These may be divided into electrical effects and temperature effects. Electrical effects include an increase in the number of

FIG. 171. Solar Corona of Sunspot Minimum Type. Drawn by H. R. Morgan of U. S. Naval Observatory

magnetic storms near sunspot maximum. These make trouble for telephone and telegraph companies, and disturb radio. Also, there are more and brighter auroral displays. As far as temperature is concerned, the weather is a little cooler over most of the United States and Europe near sunspot maximum, and as a result the growth rings of trees in the Southwest are a little thicker, and the

corn crop in Iowa is a little poorer. These effects of the solar cycle, although well established, are so small that they would be revealed only in studies covering several years.

Viewing the Sunspots. One cannot look directly at the Sun without danger of injuring his eyes, but he can protect his eyes easily by using a dark glass or enough exposed photographic negatives so that the Sun appears as a dull red rather than a dazzling bright.

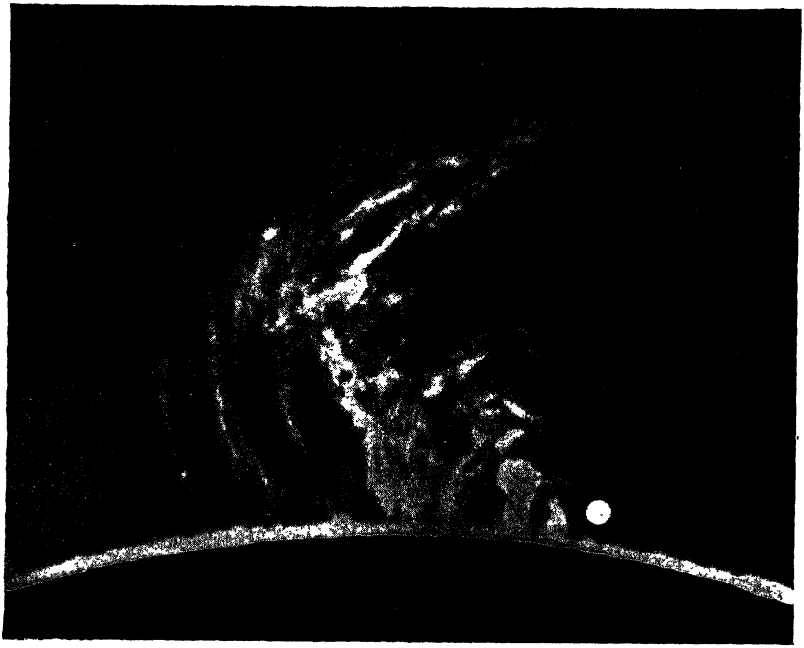


FIG. 172. Solar Prominence Photographed in Calcium Light, July 9, 1917. The height is 140,000 miles. The white dot shows the relative size of the Earth. Photograph from Mount Wilson Observatory

Usually this dull red disk appears perfectly blank to the unaided eye, but occasionally there are spots large enough to be seen easily with the naked eye.

To see the smaller spots, field glasses or a telescope can be used; but here again one cannot look directly at the Sun without protecting the eyes. The beam of light issuing from the eyepiece of even a small telescope may be sufficiently hot to set fire to paper, or to burn a blind spot in the eye.

To show the sunspots with field glasses, project the image of the Sun on a piece of white paper, like the flyleaf of a book, held perhaps two feet from the field glasses. If the field glasses are held steady by some support and the image carefully focused, spots of any size can be shown to a considerable group. With a small telescope, a larger image of the Sun can be projected in the same way to show the spots.

The Prominences. At the time of a total solar eclipse, there usually are a number of rosy clouds, or prominences, at the edge of the black disk of the Moon. These are clouds, chiefly of hydrogen, which sometimes float quietly in the chromosphere (quiescent) and sometimes fly outward with explosive speed (the eruptive).

Prominences have been observed since 1890 with the spectroheliograph, a device for photographing the Sun in the light of one element, or color. The spectroheliograph may be attached to an ordinary telescope, or used with a tower telescope built especially for work on the Sun. In recent years, the monochromator and the coronograph have been perfected, two smaller and simpler instruments for photographing the Sun in the light of one color. These are especially useful for regular exposures on motion picture film to show the motion of the prominences at a speed many times their real speed.

The Composition of the Sun. The chemist, studying the composition of a certain alloy, analyzes a sample in his laboratory. The astronomer obviously cannot obtain a sample of the Sun for the conventional methods of laboratory analysis, and the best scientists one hundred fifty years ago doubted that man would ever know the composition of the Sun. In the first half of the nineteenth century, however, spectrum analysis was developed. When light is spread out into a spectrum, it shows lines from which the elements in the source of light can be identified. This can be applied to sunlight just as readily as to light from a sample heated in the laboratory. For this work, the spectroscope is attached to the telescope.

The following are the four laws of spectrum analysis:

1. *The Bright Line Spectrum.* In a relatively rarefied gas each atom or molecule is free to vibrate in its own characteristic manner. The atom in a rarefied gas is like a violin, with the strings emitting only certain tones when caused to sound. The atoms emit light only in certain wavelengths, or frequencies of vibration, and

when the light is spread out into a spectrum, each wavelength appears as a bright line.

2. *The Continuous Spectrum.* In a solid, a liquid, or a compressed gas, the molecules and atoms are packed together closely so that the molecules and atoms cannot vibrate freely. If they are caused to vibrate, by heat, for example, the result is a jumble of all wavelengths. If this light is spread out into a spectrum by a prism, the result is a continuous band of color, red at one end with blue or violet at the other. The molecules or atoms in a solid, liquid, or compressed gas are like violins packed together in a bag. If one tries to make them sound, the strings and sounding boards cannot vibrate freely, and a mere jumble of noises results.

3. *The Dark-Line Spectrum.* If light from a highly heated solid, liquid, or compressed gas is passed through a rarefied and relatively cooler gas, the result is a continuous spectrum crossed with dark lines where there would be bright lines if the rarefied gas alone were shining. This is the type of spectrum usually obtained from the Sun. The photosphere gives a continuous spectrum, and the cooler reversing layer produces dark lines in this band of color.

4. *The Doppler Principle.* Persons who have traveled much by train have heard another train whistle as the train on which they were riding met it. There is a noticeable drop in pitch just after meeting, because as the trains are approaching, more sound waves than normal reach the ear per second, and as the trains are separating, fewer sound waves than normal reach the ear per second. Fizeau applied this principle to light. If the observer and the source are relatively approaching, the lines of the spectrum are shifted toward the blue end, and if they are relatively receding, they are shifted toward the red end. By measuring the shift of the lines of the spectrum toward the blue or the red, the rate of approach or recession in miles per second can be obtained. Blue light, with a higher frequency of vibration, affects the normal photographic film more strongly. Those who have used cameras know that a blue sweater photographs almost white, while a red sweater photographs almost black.

The Solar Spectrum. The normal spectrum of the Sun is a dark-line spectrum. The photosphere gives a continuous spectrum in itself, and the relatively rarefied and cooler gases over it absorb light, making dark lines.

At the time of a total solar eclipse, there are a few seconds just before totality, and again just after totality, when the photosphere is covered, and some of the reversing layer comes into view. These more rarefied and cooler gases are still hot enough to shine, but give a bright-line spectrum. At this time, therefore, it is possible to obtain a bright-line spectrum of the Sun.

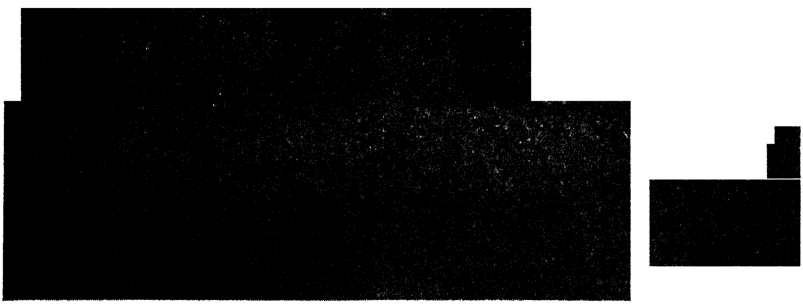


FIG. 173. Sunspot Group of September 16, 1941. Photograph from Mount Wilson Observatory

More than half of the elements found on the Earth have been identified on the Sun by lines in the spectrum. The outer portion of the Sun appears to be 90 per cent hydrogen, with much helium. The reddish prominences seen at the time of an eclipse, and at other times with a spectroscope, are largely hydrogen, but the lines of calcium are conspicuous in many of the prominences.

The element helium was found on the Sun about thirty years before it was found on the Earth. The spectral lines of this element were observed at the time of an eclipse of the Sun in 1868. It was identified on the Earth in 1895 and since then has been used extensively in dirigible balloons, and also in neon signs.

Magnesium, a light metal which is more abundant in meteorites than in terrestrial rocks, is also more abundant on the Sun than on the Earth. Perhaps, because of the relatively small size of the Earth, it has lost more of the lighter elements than the larger members of the solar system.

The Temperature of the Sun. The temperature of the Sun can be

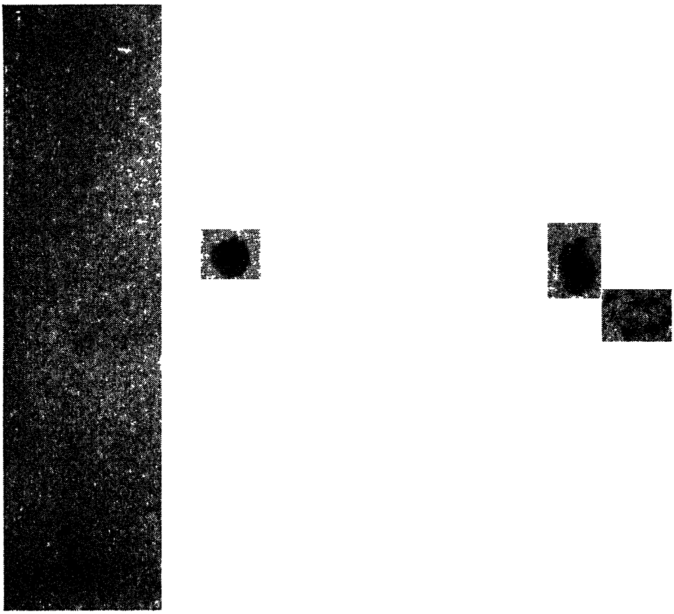


FIG. 174. Sunspot Group, October 11, 1941. This is the same group photographed September 16. Photograph from Mount Wilson Observatory

measured in three ways by indirect methods which are used in measuring very high temperatures in the laboratory or in industry.

The first method is simply measuring the heat received from the Sun. Sunlight may be allowed to fall on a mirror which concentrates the light and heat of the Sun on a bolometer or other device for measuring it accurately. These measurements must be taken in dry desert regions at high altitudes, and corrections must be entered for absorption by the Earth's atmosphere.

The second method may be considered a measurement of the predominant color of the sunlight. Sunlight is definitely bluer than

the ordinary incandescent lamp, as is shown by the so-called daylight bulbs which are tinted a very dark blue to match the color of sunlight. This shows that the Sun must be hotter than the filament of an electric light bulb. The law of change of color with temperature can be determined in the laboratory, and the temperature of the Sun or of a steel furnace can be calculated from the color of its light. Instruments called pyrometers have been

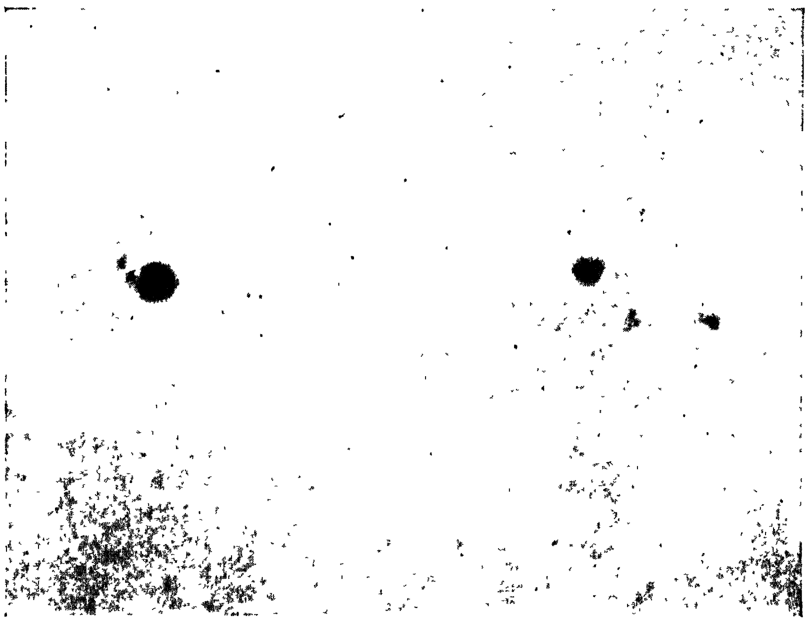


FIG. 175. Sunspot Group, October 14, 1941. Compare with pictures of the same group October 11 and September 16, 1941. Photograph from Mount Wilson Observatory

constructed so that by looking at a source of light and matching the color, the temperature can be read without calculation. The temperature of the Sun can be read directly from the color, like the temperature of a steel furnace.

The third method of measuring the temperature of the Sun is a comparison of the brightness as seen in two or more different colors, for example, red and blue. If a light bulb is shining with a dull red glow, it will look much brighter through a piece of red

glass than through a piece of blue glass. If, however, a source of light is exceedingly hot, it will look brighter through a blue glass than through a red glass. The law of change in relative brightness has been worked out accurately, and it can be applied to the Sun, using not just two colors but several colors.

The temperature of the Sun's photosphere, as determined by the three different methods, is just about 6000°C above absolute zero, the three results agreeing well. Calculations by modern physics indicate that the temperature of the deep interior must be millions of degrees centigrade. Physical theory is not completely worked out for such temperatures, but as far as it goes, it indicates temperatures of ten to twenty-five million for the interior of the Sun.

How the Sun's Heat Is Maintained. From geology it is known that the Sun has been shining on the Earth, with approximately the same intensity as now, for hundreds of millions of years. In that time an almost inconceivable amount of energy has been radiated away. Man has long speculated on how this energy is maintained.

One of the first guesses naturally was simply that the Sun is burning. Another guess was that the Creator simply had started the Sun off exceedingly hot, and that it is cooling off. A more reasonable guess suggested that the Sun's heat might be maintained by meteors falling in. None of these guesses, however, could be accepted by scientists.

The first apparently good explanation offered was that proposed by Helmholtz, a German physicist, more than eighty years ago. He assumed that the energy came from the compression of the gaseous interior by the weight of the outer layers. Compressing a gas heats it, as anyone who has pumped up a flat tire should know. Calculations by Helmholtz and others indicated that contraction of the Sun, so slow that it would take about 10,000 years to make the diameter of the Sun enough smaller to be measured by telescopes, would give a compression sufficient to generate the heat radiated.

The theory was received enthusiastically, and physicists and astronomers assumed that this was the main source of energy of the Sun and stars. About 1900, however, geologists and astronomers began to question this theory, and by 1918 most American astronomers were convinced that subatomic energy must be assumed to account for the Sun's radiation.

Modern work of physicists specializing in the study of the atom indicates that hydrogen is the "fuel" of the Sun, and that it is being transformed to other elements in the interior. As the outer layers of the Sun, at least, are about 90 per cent hydrogen, these transformations account for the radiation of energy over a quite sufficient number of years.

The Sun Is the Source of Man's Power. At the distance of the Earth from the Sun, the energy received by a square yard perpendicular to the Sun's rays is equivalent to about 1½ horsepower. The Sun's rays are perpendicular only at one point, and at any one time the Sun is only shining on half of the Earth, but if the energy received could be converted to electricity without loss, it would be sufficient to keep a 250-watt lamp burning on each square yard of the Earth's surface, including both the night side and the day side.

Though the energy of the Sun comes to us in such great quantity, it has seldom in the past been used as a direct source of power. However, all the important sources of man's power can be traced to the Sun. Coal and petroleum are derived from ancient plant life, built, as all plants are, from carbon dioxide and water by the sun-reliant process of photosynthesis. Water power and its derivative electricity depend finally on the evaporation caused by the Sun. And even man's own strength finds its eventual source in the life-giving power of the Sun.

Exercises

1. Knowing the distance from the Earth to the Sun, and the Sun's apparent diameter, calculate its real diameter.
2. Give the figures for the mass, density, diameter, and distance of the Sun.
3. Calculate the mass of the Sun in terms of the mass of the Earth by Newton's law of gravitation. Use the diameter and surface gravity of the Earth, and the diameter and surface gravity of the Sun.
4. What are the synodic and sidereal periods of rotation for the Sun at the equator?

5. List the layers of the Sun. Which is the visible surface?
6. Where are most of the sunspots on the Sun? What are they? How big are they?
7. What is the sunspot cycle, and what is its period?
8. What are some of the effects of the sunspot cycle on the Earth?
9. What are solar prominences?
10. Name some instruments which were developed especially for study of the Sun.
11. State the laws of spectrum analysis.
12. Of what spectral type is the solar spectrum?
13. What elements are the most abundant on the Sun?
14. How is the Sun's temperature measured?
15. What are some theories for the source of the Sun's energy?
16. Trace back to the Sun the more important sources of energy for our civilization.

☆ XIX ☆

The Stars

In the earlier chapters, you have read only about the members of the solar system. They are close neighbors, astronomically speaking. Even at the distance of Pluto, the most remote planet, the Sun would give over 200 times as much light as our Moon gives us when full. However, at the distance of the nearest of the night stars, visible to the naked eye from most of the United States, the Sun would appear about as bright as Polaris does to us. At the distance of this relatively near star, the most powerful telescope would not reveal the brightest of the planets. The stars are self-luminous bodies like our Sun, or we would not be able to see them, even with a telescope.

The Apparent Brightness of a Star. The apparent brightness of a star depends on three things, its size, distance, and temperature. The star Rigel appears bright because it is both big and hot, even though it is rather distant. Betelgeuse appears bright because of its enormous size, although it is one of the cooler stars, and is not especially close. Sirius appears bright because it is hot and close, even though it is not a large star.

Our Sun would be called an average star in size, and brightness, but stars fainter than our Sun in real brightness are more numerous than stars brighter than our Sun.

Star Distances. In the paragraphs on the revolution of the Earth, parallax is defined as the difference in direction of an object as seen from two different points. As the Earth moves around in its orbit, its motion causes the nearer stars to shift back and forth with respect to the background of very distant stars.

The *parallax of a star* is one-half the displacement caused by this motion of the Earth from one side of its orbit to the other. (See Fig. 52, page 114.) Knowing the diameter of the Earth's

orbit in miles and this angle, the distance of the star in miles can be obtained. For the fixed stars, the distances are too great to write in this way. It would be like expressing the distance from New York to London in inches. As a convenient unit, astronomers have taken the *light year*, which is the distance light travels in one year, about six million million miles. In some mathematical work, the distance at which a star would have a parallax of one second of arc is used as a convenient unit. This is termed the *parsec*, from the words parallax and second.

A star with a parallax of one second of arc would be at a distance of 3.26 light years or one *parsec*, so that the distance of any star is obtained from the formula

$$D = 3.26/\pi'',$$

where D is the distance in light years, and π'' is the parallax in seconds of arc.

The following are three ways of determining the parallax, or the distance, of the stars. Notice that the first method is a direct measurement, while the latter two are indirect.

1. *Direct Measurement of Parallax.* This method is used for the nearer stars. Photographs are taken throughout the year and the displacement of the nearer stars with respect to the background of more distant stars is measured microscopically. This method can be used for several hundred of the nearer stars, but for the more distant stars the displacement is too little to be measured.

2. *Spectroscopic Measurement.* From a study of the spectra of the nearer stars, whose distance can be measured directly, it has been found that a small star of a certain spectral type has a spectrum somewhat different from that of a giant star of the same type. The changes from the smallest to the largest stars of each type have been studied carefully, so that the real brightness of a star can be read from its spectrum. With the real brightness and the apparent brightness known, the distance is determined readily. The formula will be given later under Absolute Magnitude.

3. *The Period-Luminosity Law.* As you will read later under variable stars, the real brightness, or absolute magnitude of a Cepheid variable star is known from its period. Hence, if Cepheid variables are found in a certain star cluster, a comparison of the real brightness obtained from the periods, and the apparent brightness, gives the parallax or distance. The formula for the relation

between real brightness, apparent brightness, and parallax will be given later under Absolute Magnitude.

The Real Motions of the Stars. The apparent annual motions of the stars shown by their parallax and by the aberration of light

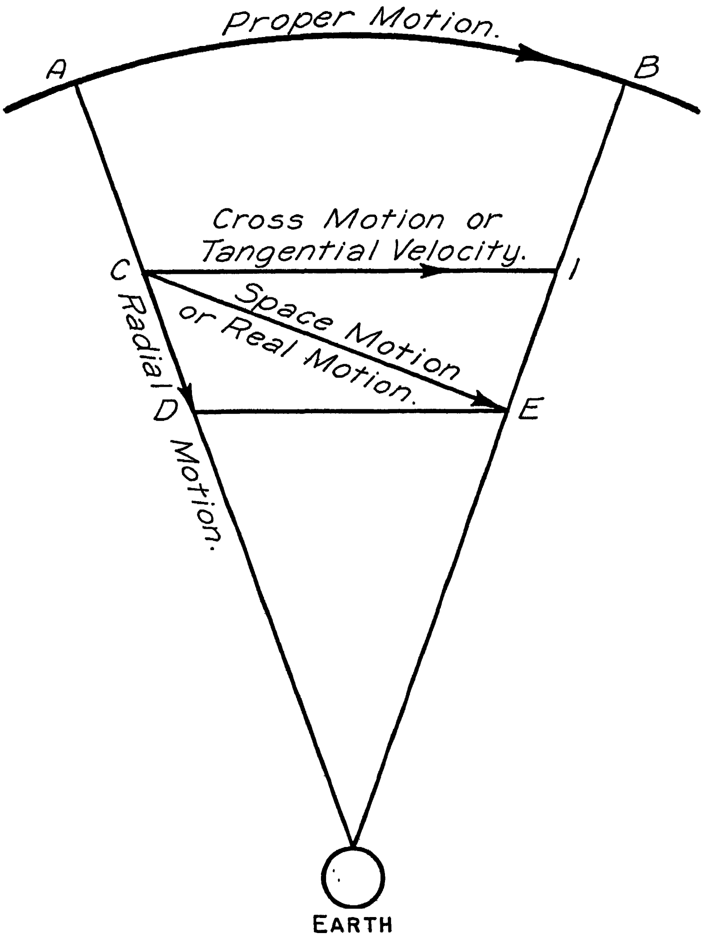


FIG. 176. The Components of the Real Motion of a Star

are not their only, or even their most conspicuous, motions. In spite of the fact that the constellation figures do not change appreciably in centuries as far as naked eye observations are concerned, the

stars are moving, and practically all have true motions of several miles per second. The great distances of the stars make these motions seem small to us, however.

The proper motion, *AB* in Fig. 176, of the stars, was detected by the astronomer Halley in 1718. He noticed that the bright stars Sirius and Arcturus had moved appreciably from their positions as indicated in the catalogue prepared by Ptolemy about 150 A.D. These have the most rapid apparent motion of any bright stars, but some faint and relatively nearer stars move even more rapidly. A rapidly moving star found by Barnard moves a distance equal to the Moon's diameter in about 180 years. This star is visible only with the telescope.

The real motion of the stars, *CE* in Fig. 176, can be broken into two components, the cross motion, or tangential motion *CI*, and the line-of-sight motion, or *radial motion, CD*. The latter is measured with a spectroscope, and can be determined rather closely in miles per second. The angular displacement or change in position per year resulting from the real motion of the star is called the *proper motion* of the star. The proper motion of a star is therefore its apparent angular rate of motion on the celestial sphere and is measured in seconds of arc per year.

The Sun's Motion. If the so-called fixed stars, or the night stars, are moving, it is reasonable to assume that our Sun, the day star, is moving also. This motion was detected by Sir William Herschel and announced in 1783.

To understand the first method of detecting the motion of the Sun let us consider a boat on a lake at night. Suppose a person, who comes from below to the deck does not know the direction of the front of the boat. As he looks around, he sees numerous lights on the shore of the lake, some apparently stationary and some apparently in motion. By watching for only a few minutes he sees that in one direction the lights are apparently closing together; in the opposite direction the lights seem to be separating or moving apart. To the right or the left, the lights as a whole seem to be moving toward the point where they close together. From this apparent motion of the lights on the shore, the observer knows that his boat is moving in the direction of the lights which apparently seem to be separating, and away from the direction in which the lights seem to be coming together.

The astronomer Herschel found that in the general direction of Vega the stars seemed to be separating, and in the general direction of Sirius the stars seemed to be closing together. This meant

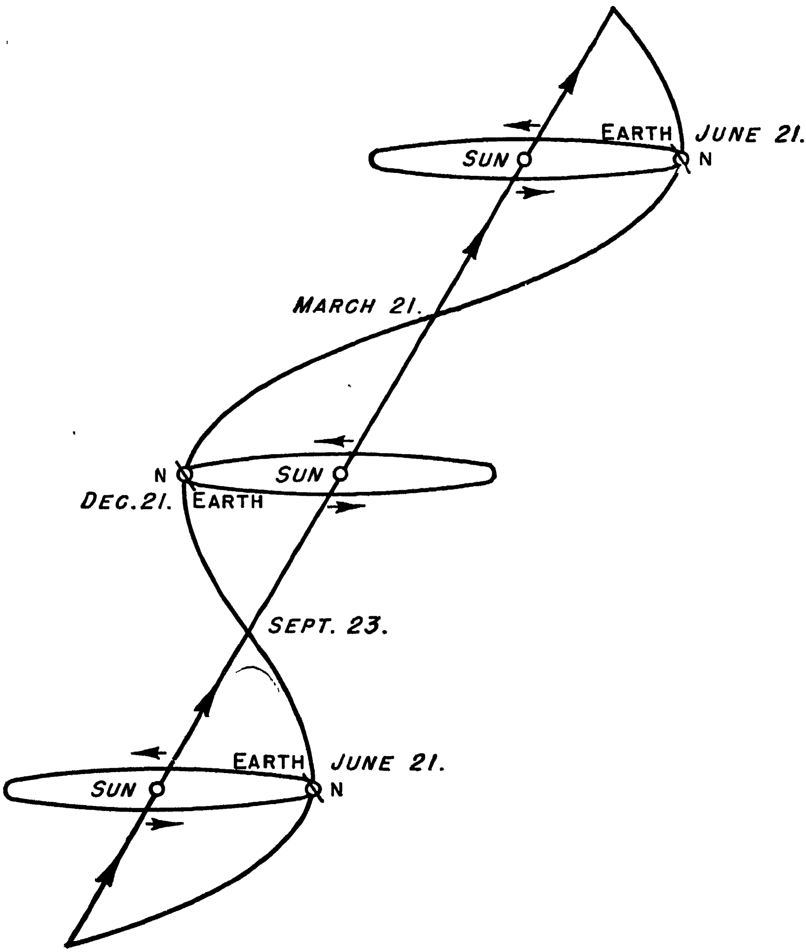


FIG. 177. The Motion of the Earth and Sun through the Local Star Cloud, the Earth moves in a Spiral

that the solar system, including the Sun, the other planets, including the Earth, is moving in a direction approximately away from Sirius and toward Vega. Fig. 177 illustrates this motion of the Sun

and the Earth. Herschel discovered the direction, but he could not measure the speed, of this motion. Since the application of the spectroscope to astronomy, however, the speed of this motion has been measured, and found to be about 12 miles per second.

Absolute Magnitude. In the paragraphs on constellations you learned the definition of magnitude, and the derivation of a formula giving the relation between the apparent magnitudes and apparent brightness of two stars. Denoting the magnitudes by m and n, and the brightness of the stars by l_m and l_n, the formula is

$$\begin{aligned} n - m &= 2.5\ (\log l_m - \log l_n) \\ &= 2.5 \log (l_m/l_n). \end{aligned}$$

It should be noted in connection with this formula that the larger the magnitude is, the smaller the brightness.

Astronomers need a term to define the real brightness of a star. For this reason they have adopted as a standard the brightness of the star as it would appear at a distance such that the parallax is 0.″1, or a distance of 32½ light years approximately. The magnitude as it would appear from that distance is termed the *absolute magnitude.*

Let $n = M$, the absolute magnitude of a star whose apparent magnitude is m and whose parallax is π. The parallax of a star varies inversely as its distance, and the apparent brightness decreases as the square of the distance increases. Hence,

$$l_m/l_n = l_m/l_M = \pi^2/(0.1)^2 = 100\pi^2.$$

Substituting this in the previous equation, we obtain

$$n - m = M - m = 2.5 \log 100\pi^2,$$

or

$$M - m = 2.5\ (2 + 2 \log\pi) = 5 + 5 \log\pi.$$

Hence $$M = m + 5 + 5 \log\pi.$$

The Spectroscopic Classes. As the stars are at great distances, their constitution can be studied only from the light which was emitted years before it reaches us. With the spectroscope, photometer, thermocouple, and bolometer, however, much information on the

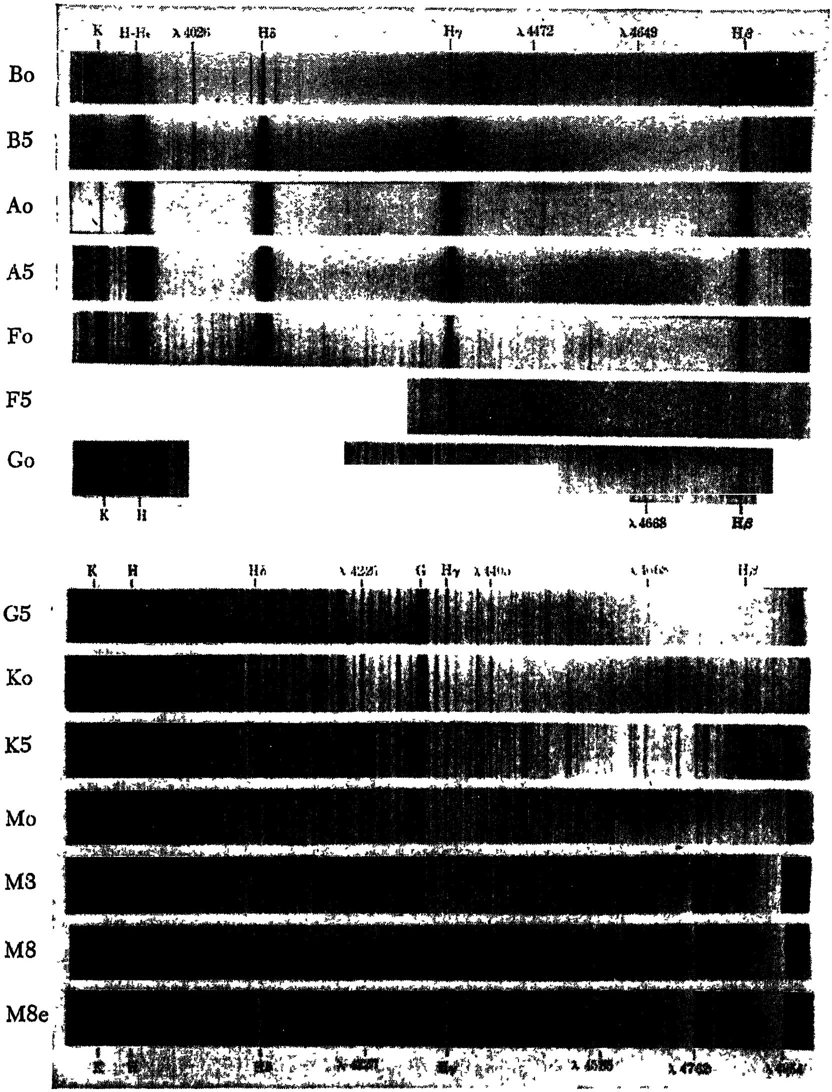


FIG. 178. Types of Stellar Spectra. Photographs by W. C. Rufus of the University of Michigan Observatory

chemical composition, temperature, and density of a star can be obtained.

The light of the stars is studied by spreading it out into a spectrum. When this is done, the lines for the bluish stars are found to be quite different from the lines for the reddish stars. The naked-eye stars are classed beginning with the hotter and bluer stars, as B, A, F, G, K, and M. On page 399 of the text two spectra are shown for each of these types, with the exception of M, for which four are shown.

Some telescopic stars of the bluish class are even hotter than class B stars. These are the class O stars. Other telescopic stars are redder and cooler than the class M stars. These are classified as R, N, and S. The spectra form a continuous sequence from the hot, bluish, class O stars to the cooler, reddish, class S stars. The following table gives for each of the naked-eye classes the approximate surface temperature, and the names of stars in that class.

TABLE XIV. THE MAIN SPECTRAL CLASSES

Class	*Temperature* (°C)	*Star*
B	12,000	Spica, Rigel, Regulus
A	10,000	Sirius, Vega, Altair
F	7,000	Canopus, Procyon
G	5,500	Rigil Kentaurus, Capella, Sun
K	4,000	Arcturus, Aldebaran, Pollux
M	3,000	Betelgeuse, Antares

It will be noticed that the letters are not in alphabetical order. The worst discordance is for the telescopic class O stars. This is because the classification was made first about 1890, when photographs of the spectra were poor. As telescopes and spectrographs improved, the classification became more accurate, and it was necessary to shift the order of the letters in several instances.

Elements in Stellar Atmospheres. With the spectroscope, the elements in the outer rarefied layers of the stars can be determined from a study of the lines shown. Hydrogen appears to be overwhelmingly the most abundant element, with helium second, and oxygen third. There seems to be more than 100 times as much helium as oxygen, and about 500 times as much hydrogen as helium. The prominence of hydrogen and helium is interesting in view of the modern theory that the heat and light of the stars is maintained by the conversion of hydrogen into helium.

The next elements in order are magnesium, silicon, sodium, aluminum, and iron. On the stars and on the Sun the lighter gases —hydrogen, helium, and even nitrogen—are much more abundant than on the Earth. It is assumed that this is because the earth was too small to hold these lighter gases when it was at a higher temperature than it is now. The light metal magnesium is more abundant in the Sun and stars than it is on the Earth, and magnesium is more abundant in meteorites than on the Earth. Except for the discrepancy in magnesium, the metals which are most abundant in the Sun and stars, are most abundant in the Earth, at least in the outer layers.

Temperature. In the paragraphs on the temperature of the Sun, you read that temperatures of luminous objects can be obtained by comparing the brightness in two colors, for example, yellow and blue. This method is used for getting the temperatures of great numbers of stars. They are photographed using film sensitive chiefly to yellow light and, then using film more sensitive to violet light. From the apparent brightness of the same star on the two different photographs, its temperature can be calculated.

The Rotation of the Stars. Although the stars are so far away that they seem mere points in the largest telescope, their rotation can be detected by the Doppler principle which was explained in the chapter on the Sun. Suppose that the telescope, with the spectroscope attached, is turned on a star which is either not rotating, or rotating very slowly. All parts of the face of the star turned toward us are approaching or receding at practically the same velocity. The lines formed by light from all parts of the face of the star will be shifted the same amount and in the same direction by this apparent motion, and the lines will have a normal appearance.

If, however, the star is rotating rapidly, the light from the center of the face of the star will be shifted by the approach or recession of the star. The lines of the spectrum formed by this light will be shifted, and the actual velocity of approach or recession will be indicated. The light from the approaching edge will form a set of lines indicating a velocity of approach as compared to the lines of the center of the star. These lines will be shifted toward the violet, as compared to the lines of the center of the star. The lines from the opposite edge will indicate a velocity of recession as compared

to the center, and they will be shifted to the red as compared to the center.

The net result of the several sets of lines, some indicating approach and some recession, is a single very wide line, the position of the center indicating the velocity of approach or recession of the star as a whole and the width of the line indicating the speed of rotation.

Diameters of Stars. The first real determination of star diameters was made for eclipsing double stars. As will be explained later, the diameters and other facts can be determined for these stars from measurements made of the light variation with the photometer and measurements of the velocity of revolution made with the spectroscope. Since there are many eclipsing stars in the heavens, a considerable number of accurate diameters have been obtained in this way.

In 1867, Fizeau suggested that the apparent diameters of stars could be measured by putting two slits in front of the telescope, so that interference fringes were formed. When the 100-inch telescope was completed at Mount Wilson about 1919, Prof. Michelson asked that a type of instrument he had suggested about 1891, the beam interferometer, be tried. It had occurred to him that if mirrors could be placed on a beam to reflect the light of the star into the telescope, star diameters could be determined in this way, the distance apart of the mirrors being used instead of the distance apart of slits on the telescope. After some preliminary experiments, a beam about twenty-five feet long was constructed, and since that time occasional measurements on the apparent diameters of seven giant and super-giant red stars have been obtained.

The following table gives the diameters of several giant red stars in millions of miles.

TABLE XV. DIAMETERS OF GIANT RED STARS

Alpha Herculis	690
Mira	395
Betelgeuse	260–360
Antares	245
Beta Pegasi	95
Aldebaran	31
Arcturus	20

Notice that the first four of these stars have diameters greater than

the diameter of the Earth's orbit. The diameter of our Sun is only 864,000, or less than 1,000,000 miles.

With a considerable number of accurate diameters determined by eclipsing variables and the interferometer, the diameter of other stars can be estimated rather closely from the light, color, and distance.

The Masses of the Stars. The mass or weight of a star is obtained from Newton's law of gravitation, that two bodies attract each other with a force that varies directly as the product of the masses, and inversely as the square of the distance between them. Obviously this law can be used only when a star or other body is close enough to a second body for the attraction to be appreciable. For the stars, this means that it can be used only on double-star systems, as the distances between stars are too great for the attraction to be measured in other cases. For double stars, the formula for the mass of a planet with a satellite can be used:

$$m_1 = m_2(p_2^2 d_1^3)/(p_1^2 d_2^3).$$

Let m_2 represent the mass of the Sun, p_2 one year, and d_2 the distance of the Earth from the Sun, or one astronomical unit. It then follows that

$$m_1 = (d_1^3/p_1^2) \text{ Sun}.$$

The subscripts can now be dropped, and the formula for the mass of a double star system becomes

$$m = d^3/p^2$$

where the period p is expressed in years, the distance d in astronomical units, and the mass m in terms of the mass of the Sun.

As an example consider Sirius and its companion. The period p is 50 years, and the distance d is 20 astronomical units. Hence

$$m = 20^3/50^2 = 8000/2500 = 3.2 \text{ Sun}.$$

This means that the mass, or weight, of Sirius and its companion taken together, is a little more than three times the mass, or weight, of the Sun.

Star Densities. With the mass or weight of a star determined, the density can be determined if the volume or size is known. The real diameters have been determined for a considerable number

of double stars of the eclipsing type, and for a few other stars large enough to be measured with the interferometer. This was explained in the paragraphs on star diameters.

With the diameters known, the volumes are known, and with the masses known as well, the densities become known, since

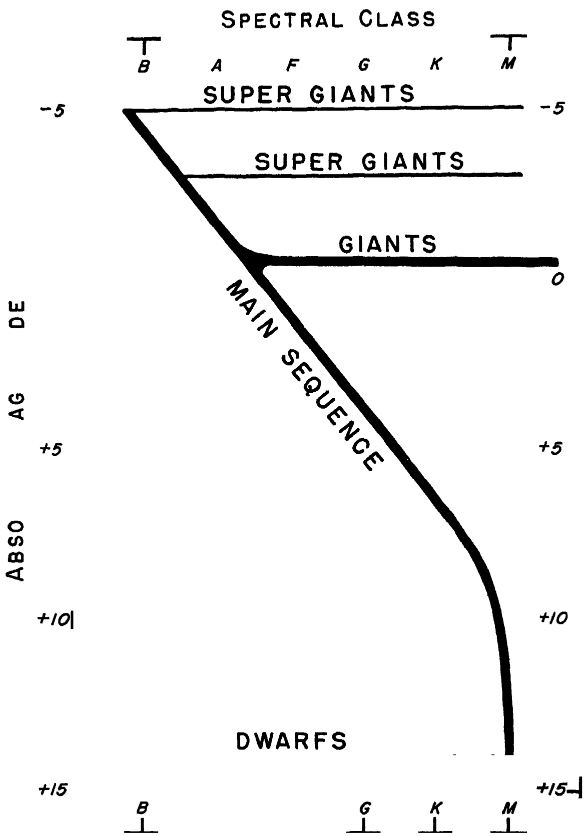


FIG. 179. The Russell Diagram of Star Brightness and Spectral Class

density is the weight per unit of volume. It is found that for some stars the density is of the order of 1/2000 the density of the air at sea level, while for others, the density must be hundreds of thousands of times that of water.

Giant Stars and Dwarf Stars. Russell announced, in 1913, that there is a definite relationship between the spectral class and the absolute magnitude of a star. If the absolute magnitude (real brightness) is plotted as the ordinate, and the spectral class as the abscissa, the stars fall on a sort of reversed *z* diagram. The giants and super-giants would fall in the upper right hand corner of Fig. 179. From these stars composed of exceedingly rarefied gas, the densities increase as one goes to the left, then down the main sequence, to the dwarfs and back along the dwarf line to the lower left corner of that diagram. The data indicates that some of the white dwarfs have densities hundreds of thousands of times that of water. A cubic foot of material from one of these stars would weigh as much as several thousand cubic feet of lead or platinum.

The companion of Sirius is a white dwarf, and is the first star for which the extremely high density was verified. The story of this interesting companion will be given in more detail in the paragraphs on double stars.

Stars are divided into the following classes according to size and brightness: super-giant, giant, main sequence, dwarf, and white dwarf. Examples of super-giants are Rigel, Deneb, and Canopus. In the table on page 406, the absolute magnitudes are given as −5.8, −5.2, and −5.1 respectively. For any distance closer than 32⅗ light years the apparent magnitudes would be smaller (greater apparent brightness) than the absolute. Venus, when its magnitude is −4, can be seen under good conditions in broad daylight, so these stars could be seen in broad daylight on clear days if as close as Vega, Pollux, or Fomalhaut. Betelgeuse when brightest could be seen in the same way if as close as Altair or Sirius.

Betelgeuse is a red super-giant, and is not quite so bright as Rigel or Deneb. It is so big, however, that if the Sun were placed at the center, the star would extend out to about the orbit of Mars. Capella is an example of ordinary giant stars; and the Sun is an example of a main sequence star. The smallest stars of all are the white dwarfs, of which the companion of Sirius, already referred to, is an example.

The following table lists for twenty-two important navigational stars, apparent magnitude, spectroscopic parallax, distance in light years, and absolute magnitude.

TABLE XVI. LEADING NAVIGATIONAL STARS

Star Name	Apparent Magnitude	Spectrum	Parallax	Distance in Light Years	Absolute Magnitude
1. Achernar	0.60	B5	″.045	72	−1.1
2. Acrux	1.05	B1	.015	217	−3.1
3. Aldebaran	1.06	K5	.051	64	−0.4
4. Alpheratz	2.15	AO_p	.028	116	−0.6
5. Altair	0.89	A5	.205	15.9	+2.4
6. Antares	1.22	MO	.014	232	−3.0
7. Arcturus	0.24	KO	.087	37	−0.1
8. Betelgeuse	0.1 to 1.2	MO	.011	296	−4.7 to −3.6
9. Canopus	−0.86	FO	.014	233	−5.1
10. Capella	0.21	GO	.071	46	−0.5
11. Deneb	1.33	$A2_p$	.005	650	−5.2
12. Fomalhaut	1.29	A3	.145	22	+2.1
13. Peacock	2.12	B3	.014	232	−2.1
14. Polaris	2.12	F8	.007	465	−3.6
15. Pollux	1.21	KO	.098	33	+1.2
16. Procyon	0.48	F5	.291	11	+2.8
17. Regulus	1.34	B8	.042	77	−0.5
18. Rigel	0.34	$B8_p$	.006	542	−5.8
19. Rigil Kentaurus	0.06	GO	.756	4.3	+4.4
20. Sirius	−1.58	AO	.377	8.6	+1.3
21. Spica	1.21	B2	.017	191	−2.6
22. Vega	0.14	AO	.121	27	+0.6

Double Stars. If one examines the stars with even a small telescope, many of those which appear as ordinary single stars to the naked eye are seen in the telescope as two or more stars. These are called double stars, and they can be divided into optical doubles and real binary stars. *Optical doubles* include those doubles that are only apparent, that is, two stars in reality quite far apart and with no physical connection, which happen to lie almost in a line as seen from the Earth. *Binary* stars are real doubles. They are those stars which are in reality close together, so that they form a physical system. Binary stars in turn can be divided into three or four classes.

1. *Visual Binaries.* Examples of visual binaries are Castor, Sirius, and Mizar. In the telescope, these stars are seen as double and in many instances the motion of one star about the other has been

sufficiently rapid to make a good determination of the ellipse since the day of telescopic measurements.

2. *Spectroscopic Binaries.* For great numbers of stars which appear single in the most powerful telescope, the spectroscope shows a periodic doubling of the lines, or a motion to and fro of the lines of the spectrum. The velocity of approach or recession can be measured from the displacement of the lines. The relative orbit of one star about the other can be computed, except that the inclination of the orbit is unknown from the spectroscope alone. Examples of spectroscopic binaries are one component of Mizar, one component of Castor, and the stars Capella and Spica.

3. *Eclipsing Binaries.* For some stars which were not known to be either visual or spectroscopic, a periodic eclipsing of the light was observed. This type of double star varies in light, and will be discussed more fully under variable stars.

4. *Interferometer Double Stars.* The beam interferometer has been applied to the measuring of star diameters. It has also been used to measure double stars. Most of these double stars, of course, can be separated in the telescope and are true visual doubles. Two double stars, however, which cannot be separated in the telescope, and consequently are not true visual doubles, can be measured with the interferometer. These stars are Capella and the brighter component of Mizar. Both of these interferometer doubles are spectroscopic binaries, however.

These classes of binary stars overlap. Every binary star bright enough to be observed spectroscopically, whose orbit is not perpendicular to the line of sight, must be a spectroscopic binary. For example, Sirius, a visual binary, Algol, an eclipsing binary, and Capella, an interferometer binary, are spectroscopic binaries as well. Every spectroscopic binary would be an eclipsing binary for observers situated nearly in the plane of its orbit. A considerable number of binaries observed first spectroscopically have been found afterwards to be eclipsing binaries. Examples of spectroscopic binaries found to be eclipsing are Beta Aurigae, Sigma Aquilae, and Lambda Tauri.

Sirius. In the 1840's, the astronomer Bessel determined this bright star to be a double from the fact that it moved in a wavy line instead of a straight line. In 1862, the companion was discovered with the telescope now at Northwestern University. Astronomers

were puzzled by the faintness of the companion star; from its color and its mass, it should be only a little fainter than Sirius if it was of the same density. Actually it emits only about 1/10,000 as much light and can be seen only with large telescopes. Its period is 50 years, and it is closest to Sirius in 1944.

The mass of the companion of Sirius must be about the same as that of the Sun but its diameter only about four times that of the Earth. Calculating the surface gravity by the formula given in the chapter on the Moon, one finds that it must be about 20,000 times that on the Earth. A pound mass on Earth would weigh about ten tons on Sirius' companion.

According to the theory of relativity, such an enormous gravitational pull should shift the lines of the spectrum toward the red. In 1925, the large shift predicted was observed, thus confirming the high density suspected. The mean density must be some 30,000 times that of water, or a quart of the interior of this star would weigh about 30 tons at the surface of the Earth.

Variable Stars

All of man's knowledge of the stars has been obtained from their light. One of the instruments which can be attached to the telescope is the photometer, which measures accurately the variations and intensity of the light. The photometer has shown that the brightness changes appreciably for hundreds of stars. These are the *variable* stars. Astronomers divide them into five classes—eclipsing, Cepheid, long-period, irregular, and novae or temporary.

The *eclipsing stars* are double stars, not real variables, but because they vary in light for us they are also listed as variable stars. We are practically in the plane of the orbit of the system, so that as the components revolve about one another, one eclipses the light of the other. The other four classes are real variables so that their light would vary for any observer who could see them.

Eclipsing Stars. The star Algol, in Perseus, was the first discovered of the eclipsing type. Its variation in light was discovered in 1670, and it probably was known even earlier, for it was known to the Arabs as the "Demon's eye." In reality Algol is two stars with each star eclipsing the other once in 2 days, 21 hours. Algol's light curve is shown in Fig. 181. Other eclipsing stars with relatively short periods are Beta Aurigae, a rather bright star near Capella, for

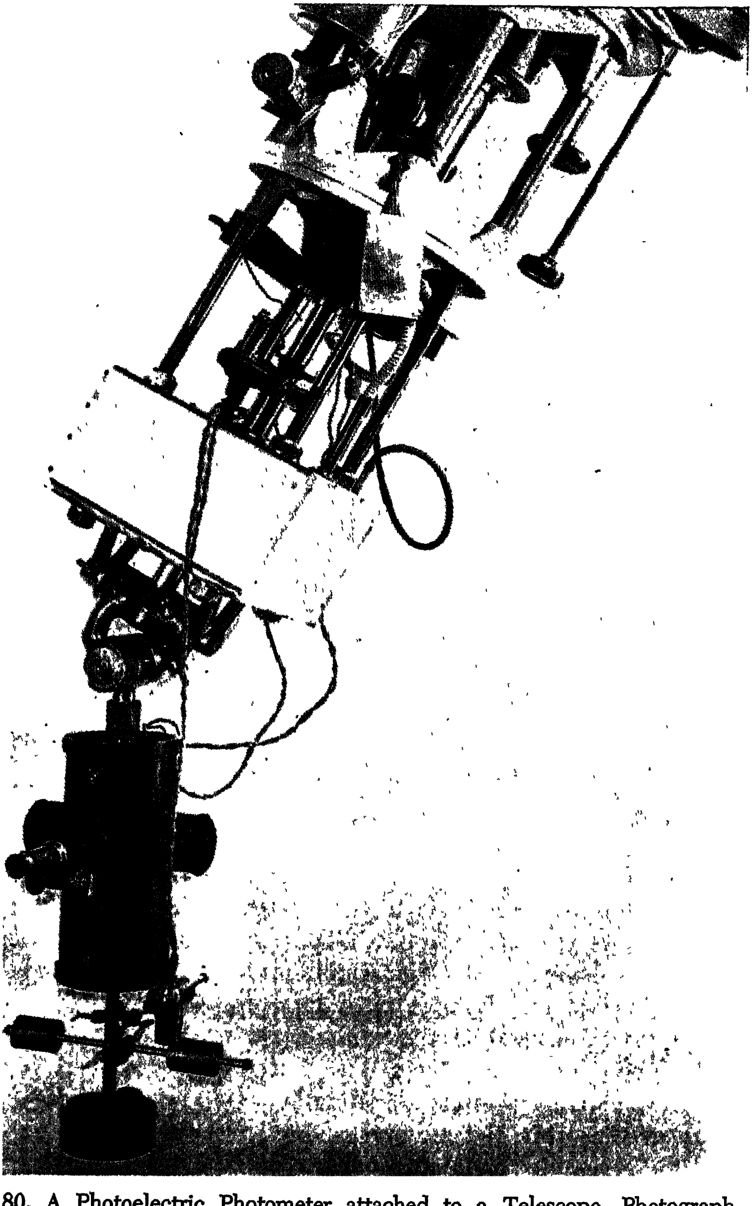


FIG. 180. A Photoelectric Photometer attached to a Telescope. Photograph from Washburn Observatory

which the period of revolution is 3 days, 23 hours, and Sigma Aquilae for which the period of revolution is 1 day, 23 hours. It is interesting that two of the eclipsing variables with the longest periods known are in the little triangle in Auriga near Capella. These are Zeta Aurigae, with a period of 2 years, 8 months, and Epsilon Aurigae with a period of 27 years.

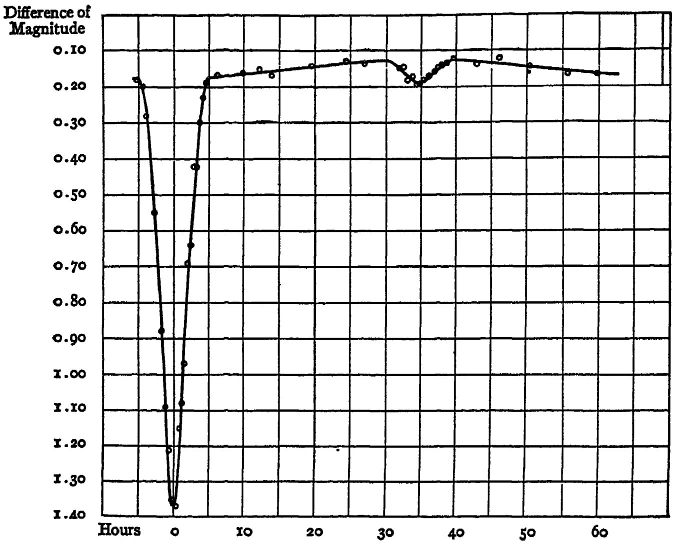


FIG. 181. The Light Curve of Algol derived by Joel Stebbins. From the *Astrophysical Journal*

Eclipsing stars are binary stars, as you have read. When the components are bright enough to be observed with the spectroscope, these measurements can be combined with photoelectric measurements of the variation in light to obtain very complete information about the system. This can be done even though no telescope in the world can separate the components visually or photographically. The information obtained includes the diameter of the orbit, and of each component; the inclination of the plane and the ellipticity of the orbit; the fraction eclipsed, relative brightness, mass, and the density of each component.

Cepheid Variables. These variable stars take their name from the first star of this type known, Delta Cephei in the constellation

Cepheus.[1] Another rather bright Cepheid variable, Eta Aquilae, was discovered almost as soon as Delta Cephei. A light curve of this star, obtained with a photoelectric photometer, is shown in Fig. 182. Notice the irregularity on the downward slope of the curve. This is a permanent "bump" because photoelectric measurements several months apart repeat this "bump" accurately.

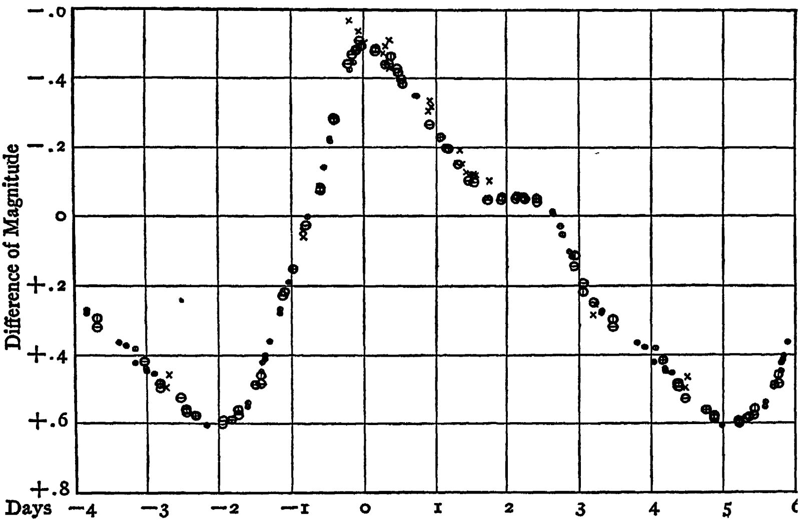


FIG. 182. The Light Curve of the Cepheid Variable Eta Aquilae

The cause of this variation in light is not fully understood, but it is quite certain that the Cepheid variables are giant yellowish stars which are pulsating, that is expanding and contracting. As they contract, the compression makes them a little hotter, increases the light, and shifts the spectral type toward the blue, or B type, stars. As they expand, they are cooled a little, emit less light, and the spectral type is shifted toward the reddish, or M type, stars.

Relation of Period to Brightness. In 1911, Miss Leavitt of Harvard announced that the period varies with the absolute magnitude for Cepheid variables. The bigger and brighter the Cepheid variable, the longer the period.

In 1918, Dr. Shapley, now Director of Harvard Observatory, used

[1] Notice that although the constellation name is pronounced with a long ē, the adjective Cepheid is pronounced with a short ĕ.

this fact to prepare a curve from which, with the period of any Cepheid variable known, the absolute magnitude could be read off. The distance of the Cepheid variable could be obtained as follows: determine the period, and read from this curve the absolute magnitude. The apparent magnitude is known from the apparent brightness. Having the absolute, or real, magnitude and the apparent magnitude the distance can be calculated readily. The formula was given in the paragraphs on absolute magnitude.

This method of determining star distances, the period-luminosity law which was referred to on page 394, is one of the most powerful for work on the more distant star clouds of our stellar system.

Long-Period Variables. The best known and first discovered of the long-period variables is Mira in Cetus. The period of this star is 330 days. At its brightest, it may be nearly equal to Polaris and at its faintest it is about ninth magnitude. As you have read, Mira is the second largest of the measured giant red stars, being some 395 million miles in diameter. This diameter, measured only at light maximum, is more than the diameter of the orbit of Mars.

The long-period variables are relatively cool stars, barely hot enough to shine, so the change in light is very great for a relatively small change in temperature, just as a small increase in the temperature of a radiant heater makes it glow much more brightly. This can be checked by measuring the radiation of Mira with a delicate thermocouple which is affected by the heat as well as by the visible light. This shows that the total radiant energy leaving the star Mira varies little more than the radiant energy leaving a Cepheid variable whose light changes only about a magnitude. The present theory is that the long-period variables, such as Mira, are pulsating stars similar to the Cepheids, although not quite so regular.

Irregular Variables. The giant red stars, being barely hot enough to shine, are more unstable than the hotter stars. The percentage of variables increases as one goes from the blue Class B stars to the red Class M stars. Betelgeuse is the best known variable star of this type. The light variation is, in general, small and cannot be predicted. It has been found that for Betelgeuse the changes in light are associated with changes in diameter of more than 50 per cent, indicating a sort of pulsation, but no theoretical explanation has been formulated.

Novae, or Temporary Stars. The term nova, or temporary star, is applied to a star which, after an indefinitely long existence without noticeable change in brightness, suddenly increases in light by perhaps hundreds of thousands of times. Ordinary novae attain an absolute magnitude of -5 to -9. Supernovae may attain magnitudes from a -14 to a -16. After a short period of brilliance, the nova drops slowly back to its former magnitude.

The nova which appeared in Cassiopeia in 1572 was for a time bright enough to be visible to the naked eye in broad daylight.

On June 8, 1918, the brightest nova of modern times appeared. For many years it had been a star of the magnitude 11. A photograph taken on June 6 showed it as magnitude 6. On the night of June 8, it was about magnitude 0, or about as bright as Arcturus or Vega. On the nights of June 9 and June 10, it was almost as bright as Sirius. This nova was the brightest star in the sky for a few nights. At its brightest, its absolute magnitude reached about -9. This means that if as close as Sirius, the closest star visible to the naked eye for us, the nova would have given as much light as the quarter Moon.

A supernova appeared near Zeta Tauri in 1054 A.D. which was visible in broad daylight for 23 days. It must have reached absolute magnitude -16, which means that if as close as Sirius, it would have been as much brighter than the full Moon as Venus is brighter than Aldebaran. This supernova is visible now in the telescope as the Crab Nebula.

Several supernova have been discovered in other galaxies, or stellar systems, than our own. The first of these appeared in Andromeda in 1885. The average absolute magnitude attained is -14.

Exercises

1. Why are some stars brighter than others?
2. Explain the three methods of measuring stellar distances.
3. If the parallaxes of Sirius, Polaris, and Aldebaran are $0.''377$, $0.''007$, and $0.''051$ respectively, calculate their distance in light years.

4. Explain how astronomers detect and measure the motion of the stars, and the motion of the Sun among the stars.
5. What is the absolute magnitude of a star?
6. Calculate the absolute magnitude of Vega and Rigel using the parallax and apparent magnitude as given in table XVI and the formula on page 398.
7. List the spectral classes and name some bright stars belonging to each class.
8. Explain how stellar diameters are measured and give the diameters of some bright stars which have been measured.
9. If the distance of the components in a double-star system is 400 astronomical units and the period is 300 years, calculate the mass of the system in terms of the mass of the Sun.
10. Where would Rigel and Betelgeuse be placed on the Russell diagram? (Fig. 179.)
11. Name four classes of binary star systems.
12. In how many ways can binary stars be detected?
13. Name the classes of variable stars.
14. Which of the navigational stars belong either to the variable class or to the binary class?
15. What is the period-luminosity law? How was it discovered and what use is it to the astronomer?
16. Explain the differences between a giant star and a dwarf star.

☆ XX ☆

Our Galaxy and Others

The term *galaxy* originally was used as a synonym for the Milky Way. Then it was extended to include the entire system of stars around us, of which the star clouds of the Milky Way are the most prominent feature. Our galaxy, or galactic system, includes what many astronomers of about 1900 referred to as "our universe" or the "visible universe."

Most of the stars visible to the naked eye appear single, but you have read already that many are double in reality. In addition, the stars are grouped into great clusters and gigantic clouds. Between, and mingled with these clusters, are huge clouds of gases and dust called nebulae. It is known that the spiral "nebulae" are distant systems of stars similar to our own Milky Way system, or galaxy. They are other galaxies, or galactic systems.

Star Clusters

The brighter stars are spread out more or less at random, but even to the naked eye some clustering is evident, as in the Pleiades and Hyades. With field glasses, many more clusters are evident, as Praesepe in Cancer, and the cluster in Perseus. These clusters are classified into the open, or galactic, clusters, the moving clusters, and the globular clusters.

The Open Clusters. Over three hundred clusters of this type are known, the numbers of stars varying from less than one hundred to several thousand. Among the better known of the open clusters are the following:

Table XVII. Some Open Clusters

Hyades (in Taurus)	120 light years away
Coma Berenices	270 light years away
Pleiades	500 light years away
Praesepe (in Cancer)	500 light years away

The *moving clusters*, or groups, include many open clusters so close that they appear scattered and are recognized only after a study of their motions and distances.

The bright stars in the Hyades (except Aldebaran), and others, form a moving cluster, consisting of about one hundred stars. This cluster is approximately globular, and about thirty-five light years

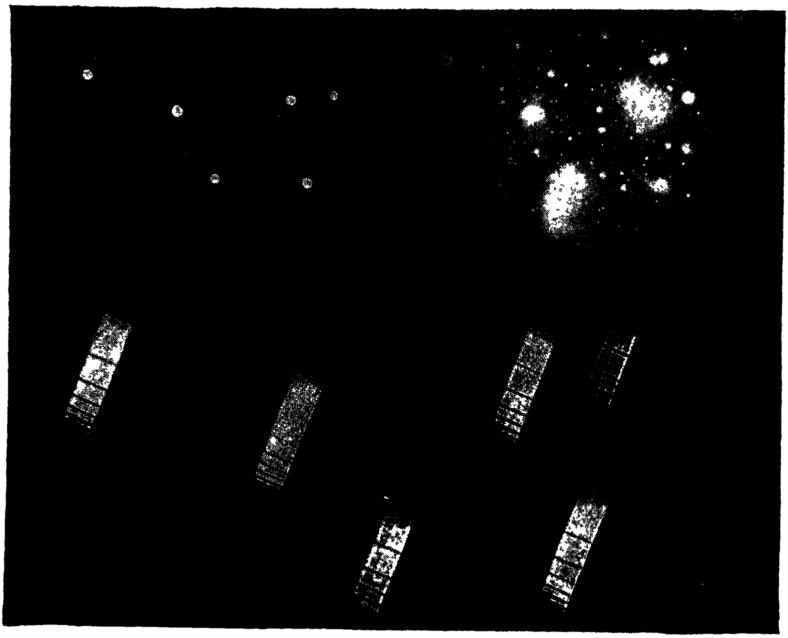


FIG. 183. The Pleiades as a Cluster, as Nebulous Stars, and as Spectra. Photograph from Yerkes Observatory and University of Chicago Press

in diameter. It is receding from the solar system, and millions of years hence will appear as a globular cluster. Several other moving clusters are known including the Pleiades, and groups of stars in Perseus and Orion.

One of the most interesting of the moving clusters is the Ursa Major group, through which the Sun is now passing as an interloper. This group, or cluster, includes most of the stars in the Big Dipper, and Sirius, Alphecca (Alpha, Coronae Borealis), Beta Aurigae, Delta Leonis, and other stars in widely separated parts

of the sky. These stars do not appear as a cluster now, but when this group has receded to a distance of some 10,000 light years

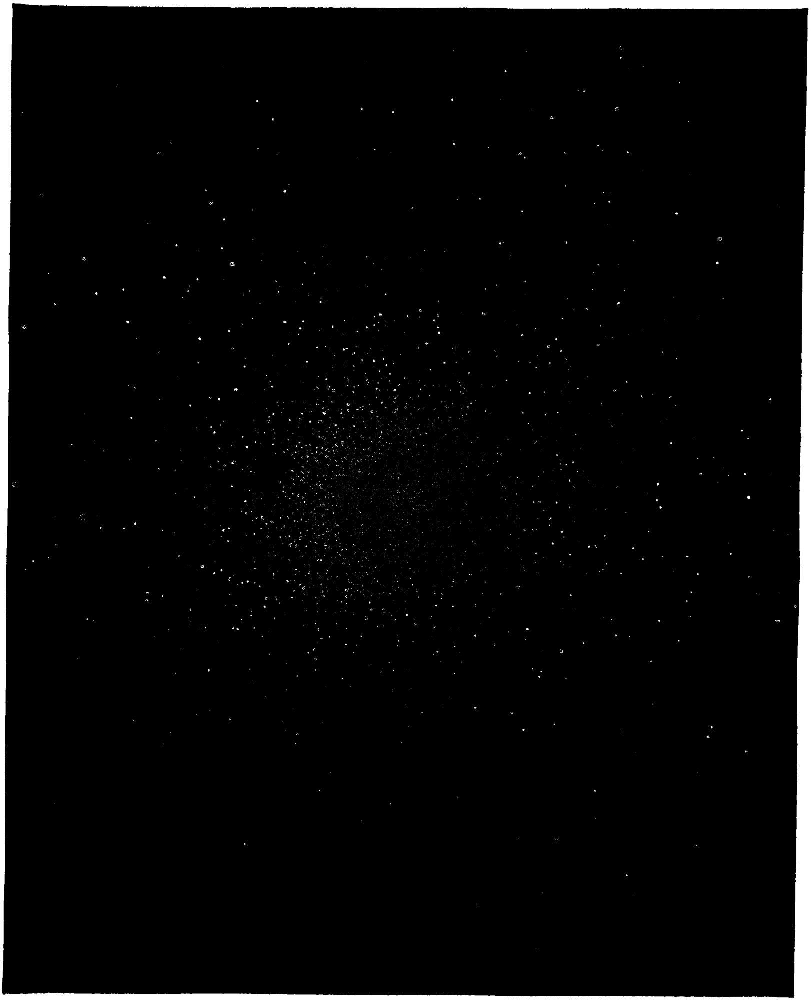


FIG. 184. The Globular Cluster M13 in Hercules. Photograph from Mount Wilson Observatory

from the Sun, the apparent distance of Sirius from those stars of the Dipper will be less than a tenth of the present distance between the Pointer stars.

Globular Clusters. These are compact, nearly spherical, swarms of stars, which are usually concentrated at the center. They are splendid objects for a large telescope. Ninety-four of these objects are known, nearly all being found in one hemisphere of the sky. The nearest globular clusters are about 20,000 light years distant, and the most remote may be more than 200,000 light years distant. The diameters are about 100 light years for the more conspicuous portion.

The two best-known globular clusters are Omega Centauri, 22,000 light years away, and the cluster M13 in Hercules, 34,000 light years away. The number of stars in M13 has been estimated as 10,000,000.

Naming Star Clusters and Nebulae. Some of the brightest star clusters, those for which some individual stars can be seen with the naked eye, are referred to by proper names. Examples of these are the Pleiades and the Hyades in Taurus, Coma Berenices, and Praesepe in Cancer. As with the stars, however, the fainter naked-eye and the telescopic clusters are indicated by the catalogue and the number in the catalogue. Since the earliest observers could not distinguish between nebulae and distant star clusters, their catalogues included both classes of objects.

The first such catalogue, and the one used for most clusters and nebulae appearing as hazy spots to the naked eye or with field glasses, was made by Messier, a French astronomer. On star charts, the clusters and nebulae catalogued by Messier, are indicated by the abbreviation M, for Messier, followed by the number in his catalogue, as for example, M13, the great cluster in Hercules. The *New General Catalogue* of Dreyer, another commonly used list, is abbreviated to N. G. C. The N. G. C. numbers do not appear on an average chart, but are used in textbooks.

Nebulae

In early times the word *nebula* was applied to the numerous patches of misty or cloud-like appearance seen in the sky. The telescope resolved many of these so-called nebulae into star clusters, or clouds of rather closely grouped stars too far away for the individual stars to be seen with the naked eye.

Green Nebulae and White Nebulae. In 1791, however, Herschel announced that the so-called nebulae could be divided into two

general classes. He was convinced that nebulae of the *green* type were composed of a "shining fluid" of a nature unknown to us, and that no telescope ever could resolve them into stars. Herschel called the second type of nebulae the *white* nebulae. In appearance these resemble distant star clusters observed with a telescope too small to show the separate stars. Herschel felt that these were not true nebulae, but distant clouds of stars which someday might be seen as swarms of stars with more powerful telescopes. Following Herschel, as more powerful telescopes were developed, more and more of the so-called nebulae were resolved into swarms of stars. Lord Rosse's great telescope, completed about 1845, showed for the first time that a considerable number of Herschel's "white" nebulae were *spiral* in form.

The Spectra of Green and White Nebulae. In 1864, not quite 20 years after the observations of Lord Rosse, the spectroscope showed that Herschel's division of the nebulae into green and white was a real division. Those of the green type showed bright lines, indicating a shining rarefied gas. The so-called nebulae of the white type showed a dark-line spectrum, with the dark lines blurred, as in any distant star cluster. In other words, the white nebulae appeared, from the spectroscope, to be distant clouds of stars.

For the next 50 years astronomers knew that the nebulae shining with the greenish, ghostly light were composed of glowing rarefied gases. Many astronomers believed that spiral "nebulae" were distant star clouds, or "island universes," as Herschel had suspected. Other astronomers were inclined to doubt this, since the most powerful telescopes in the world at that time, including the 40-inch Yerkes, had failed to resolve any of these so-called spiral nebulae into individual stars.

Spiral "Nebulae" Are Systems of Stars. In 1919, the 100-inch telescope was completed, and Dr. E. P. Hubble began work on the nebulae, including the spiral nebulae, with this telescope. This great instrument was much more powerful than anything in use before that time and work with it showed conclusively that M31, the Spiral Nebula in Andromeda, was not a real nebula but a distant system of stars comparable in size to our own. This system, M31, will be taken up more fully later.

Modern investigators divide nebulae as a whole into two classes,

galactic nebulae, the nebulous material in our own stellar system, and *extra-galactic nebulae,* the spiral nebulae, which are exterior systems of stars.

Galactic Nebulae. The nebulosity in our stellar system has been divided into the *planetary nebulae* and the *diffuse nebulae.* The

FIG. 185. The Ring Nebula M57 in Lyra. Photograph from Mount Wilson Observatory

diffuse nebulae in turn can be divided into the bright, or self-luminous, the reflection, and the dark.

Of the *planetary nebulae,* about 130 are known. These are faintly luminous disks of light, oval or nearly circular in shape. Usually there is a relatively faint star at the center and the disk is brighter at the edge, suggesting a ring. These objects are nebulous envelopes surrounding a star whose light is partially obscured by

the nebulosity, and in general they are in rotation. It has been suggested that the planetary nebulae are the result of an explosion

FIG. 186. The Great Nebula in Orion. Photograph from Mount Wilson Observatory

of the central star. The Ring Nebula in Lyra, M57, is one of the best known examples.

Diffuse Nebulae. Those in our galaxy vary in brightness from relatively bright clouds, as the Great Nebula in Orion, M42, or

the Trifid Nebula, through the almost imperceptible haze, as the nebulosity in the Pleiades, to the definitely dark obscuring clouds, as the Horsehead Nebula near Zeta Orionis. The explanation for this variation in the appearance was found by Dr. Hubble to be the stars, if any, in the nebulosity.

If the nebulous material is near a very hot star, hotter than B_1, it is bright, and it shines with a light similar to the aurora or northern lights in our own sky. The nebula in the sword of Orion, M42, is the most conspicuous of the self-luminous, or bright, nebulae.

If nebulous material is near an average star, one cooler than B_1, it shines by *reflection*, like the clouds in our own sky. The nebulae in the Pleiades and the Network Nebula in Cygnus are good examples of reflection nebulae. These shine so faintly that they cannot be seen visually, but show up well on long exposure photographs.

If nebulous material is not near any star, it is dark. *Dark nebulae* are revealed on photographs. The Horsehead Nebula in Orion is a conspicuous example of the dark nebulae.

About 1864, as you have read, it was found that the spectra of the bright galactic nebulae show bright lines, but the lines could not be identified. The chief lines were attributed to a hypothetical element "nebulium." About 1925, it was suggested that out in space the gases in the nebulous material might be in such a rarefied state that lines would appear which could not be duplicated in a laboratory. A physicist, therefore, calculated, from the observed spectra of the elements, what lines would be produced in an exceedingly rarefied state. These calculations showed that the lines of "nebulium" were due to oxygen and nitrogen in a very rarefied state, the density perhaps being only one-trillionth that of air at sea level. These elements in nebulium are the chief gases in air, so it was announced that nebulium had literally vanished into "thin air."

The galactic nebulae contain hydrogen and helium also, and by studying the stars that shine through clouds of nebulous material, it has been found that calcium and sodium are present also. The real nebulous material is largely gaseous, but the study of the light of stars shining through it shows that it includes solid material,

dust or tiny meteors. A nebula, therefore, is a cloud of gases and dust.

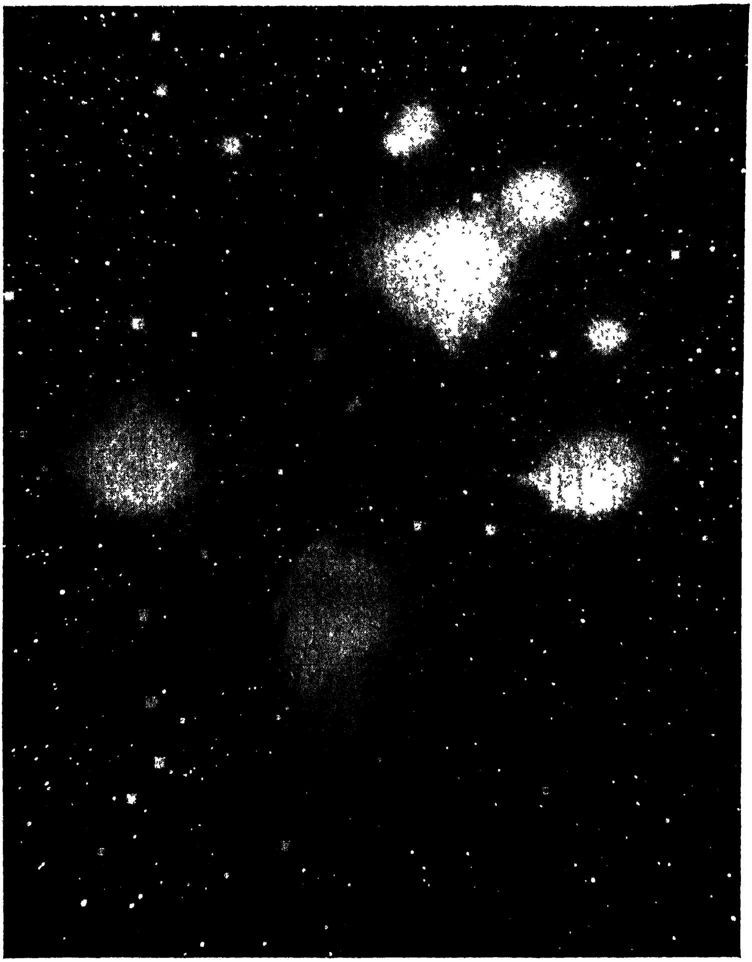


FIG. 187. Nebulous Material in the Pleiades. Photograph from Yerkes Observatory and University of Chicago Press

The Crab Nebula. This nebula, M1, near Zeta Tauri, is a bright irregular nebula, of special interest because studies have revealed its probable origin. In 1054 A.D., a supernova appeared near Zeta

Tauri, which, according to Chinese records, was visible in broad daylight for 23 days, and to the naked eye for about 650 days. The Crab nebula is now expanding rapidly, and calculations indicate that the explosion which produced it must have occurred about 1054. There is no real doubt that the supernova of that year is responsible for this nebula. See Fig. 188.

Mapping Dark Diffuse Nebulae. The first mapping of the regions

FIG. 188. The Crab Nebula, M1, in Taurus. Photographed at Mount Wilson Observatory

of dark nebulosity was done by photography. For numerous regions, it is obvious that stars in the background are wholly or partially obscured. Next, the spectroscope was used. The spectra of all the stars behind a cloud show the lines of the material in the cloud. The regions of Orion and Cepheus, for example, are covered with nebulous material, much of it dark, and including calcium and sodium.

More recently, the photoelectric photometer has been used to

measure the reddening effect of the nebulous material. Stars seen through such a cloud are redder than normal. The reddening effect

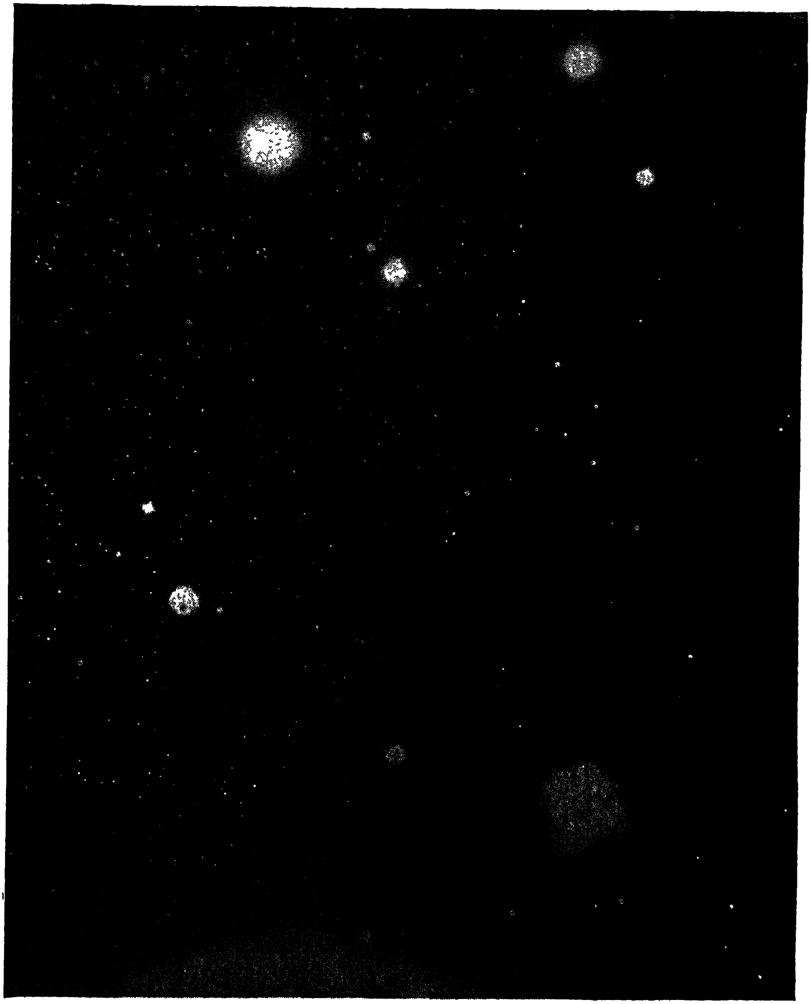


FIG. 189. The Horsehead Nebula near Zeta Orionis. A dark cloud obscures more distant stars in right of the picture. Photograph from Mount Wilson Observatory

is determined by measuring the color of a star and comparing this color with the spectral type as determined by the spectroscope.

A B-type star behind such a cloud will not be as blue as a normal B-type star. In fact, some B-type stars have been found to be as

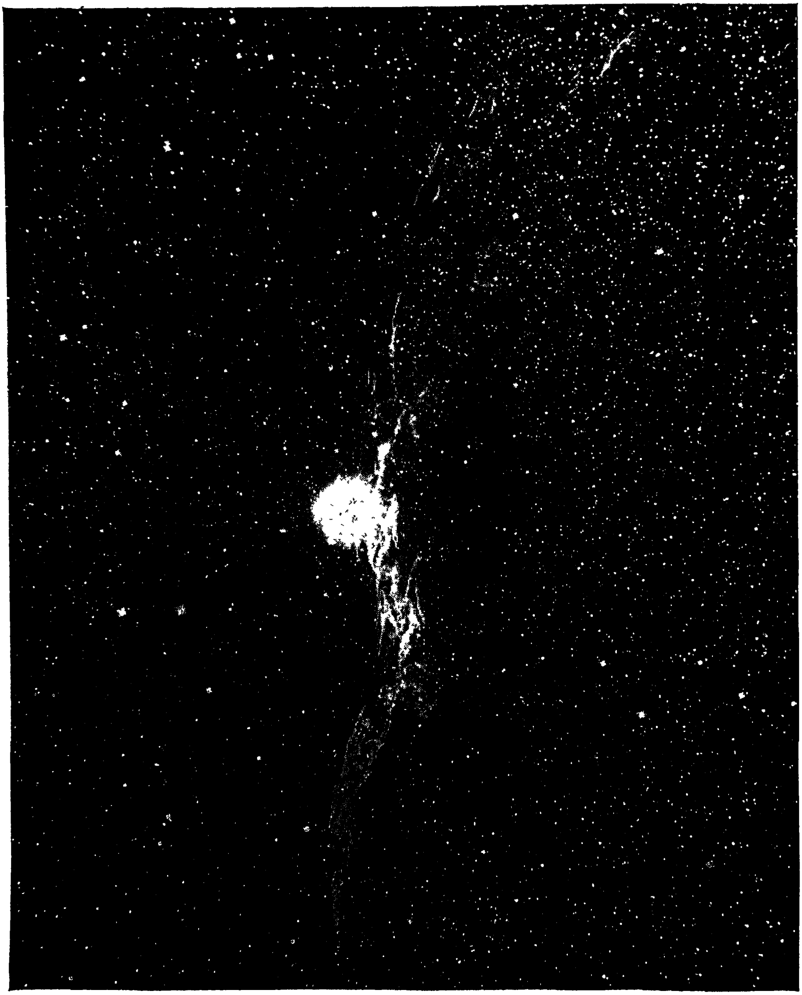


FIG. 190. The Filamentary Nebula in Cygnus. Notice the meteor trail to the left. The nebulous material extends to the left of the filament, and partially obscures the stars on that side. Photograph from Mount Wilson Observatory

red as M-type stars. For such a reddening, it can be calculated that only about one per cent of the light of the star is coming through

the cloud of nebulous material. The photoelectric is probably the most accurate method of mapping in use now.

OUR GALAXY

The Shape of Our Galaxy. The first work on outlining the general shape of the Milky Way system, or our galaxy, was started by Herschel in 1784. Pointing a telescope in all directions, he merely recorded the number of stars he could see in the field of his telescope. For simplicity, Herschel assumed that the stars were distributed uniformly in space as far out as they extend. The assumption of uniform distribution meant that the distance to which the stars extend is proportional to the cube root of the number of stars counted in that direction. The counts showed that the stars extend much further in the direction of the plane of the Milky Way than in a direction perpendicular to that plane. Herschel's result was that the galactic system must be shaped like a grindstone, with its edges in the direction of the Milky Way.

Preliminary Work on Size of Galaxy. Herschel's work gave the approximate shape of the galactic system, but the size was quite unknown then since no star distances had been measured. It is obvious that if the distances of stars in the various clouds and clusters could be measured, a model could be constructed which would give the shape and size with some accuracy.

There are three methods of determining star distances (page 393). The star clouds of the Milky Way are too distant for direct measurement, or even for the spectroscopic method. The period-luminosity law (page 394), however, can be used. In 1918, Shapley applied this method to star clusters in all parts of our galaxy. From this work he constructed a preliminary model, which represented our galaxy as some 1,000 light years thick, and 200,000 light years in diameter.

Effect of Dark Nebulous Material. In pioneer scientific work it is customary to make certain simplifying assumptions until a preliminary picture is obtained. In his preliminary work Shapley obtained the distances from the apparent and absolute magnitudes, neglecting possible absorption of light by nebulous material. Of course, a star seen through nebulous material would appear fainter, and hence more distant than it is in reality.

About 1930, the importance of nebulous absorbing material became apparent. Some astronomers began work on this problem with the spectroscope. They found the spectra of stars in Orion showed some of the stars alternately approaching and receding. At the same time the spectra showed stationary lines of calcium,

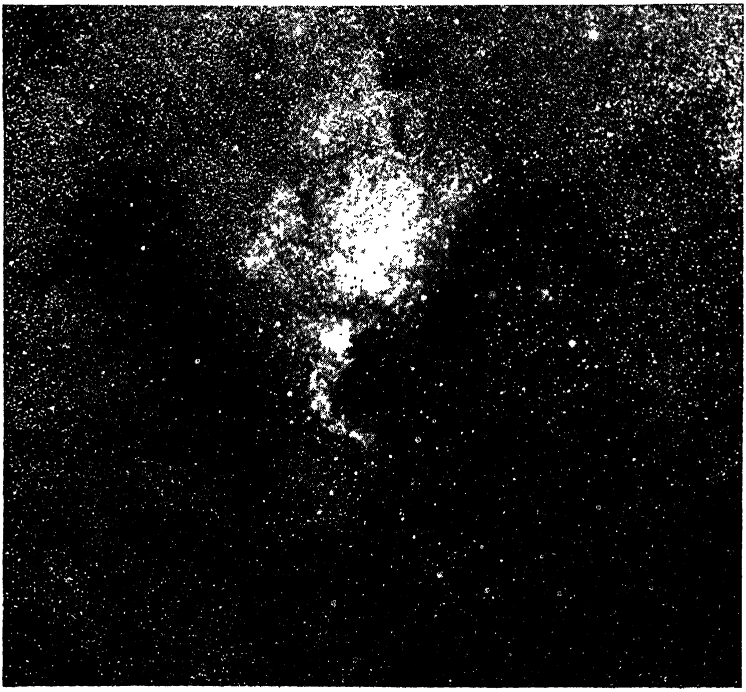


FIG. 191. The North America Nebula in Cygnus. Photograph from Yerkes Observatory and University of Chicago Press

indicating stationary clouds of dark calcium in front of the stars. In the same way they found clouds of dark material covering much of Cepheus.

Stebbins began photoelectric work on the problem. By using the two different cells, a potassium cell which gave results very nearly the same as photographic work, and a sodium cell, which gave results very nearly the same as visual, he determined the colors of stars all over the sky. He knew that normally a G-type star should

have a yellowish color, and a B-type should have a bluish color, but over certain areas he found that the stars were reddened considerably, like the setting sun, indicating that nebulous material had absorbed much of the light. From the reddening he could calculate how much light had been lost. By correcting the apparent magnitudes for the loss of light and then comparing them with the absolute magnitudes, more correct distances can be obtained. Shapley's preliminary figures were reduced when revised by this work.

Revised Figures for Size. Recent papers adopt 100,000 light years as the diameter of our galaxy, and 5,000 to 15,000 light years as the thickness. The thickness is greater at the center, and less toward the edge. (See Fig. 192.)

The Number of Stars. There are three ways of approximating the total number of stars. The first is to use counts of stars of various magnitudes. From these counts a curve can be constructed and extended to include the stars not visible in any telescope. By this method, an estimate of thirty billion as the total number was made some twenty years ago.

A second method is the construction of a model (at least mathematically). In each star cloud the observed stars, only the brightest, are placed. From the number of bright stars, and other considerations, the number of fainter stars can be estimated and filled in. About 1922, Kapteyn, an European astronomer, completed such a model and announced 47 billion stars as his estimate of the total number. Since 1930, however, the astronomers have been making laborious corrections for absorbing material, as indicated in a previous paragraph. Allowing for stars behind these dark nebulous clouds, they are giving 100 billion as the estimated total number of stars.

The law of gravitation furnishes another method of attacking the problem. It does not give the number directly but it does give the mass. If one knows the rate at which stars at different distances from the center of our galaxy are moving, he can calculate the mass of the stars in the central regions of our galaxy, and then the total mass of the whole galaxy. From the total mass, the number of stars can be estimated. This method furnishes a useful check on results obtained from models.

The Local Cloud. For more than one hundred years it has been known that our Sun is in a cloud of stars, similar to the clouds we see in the Milky Way. Most of the stars we see with the unaided

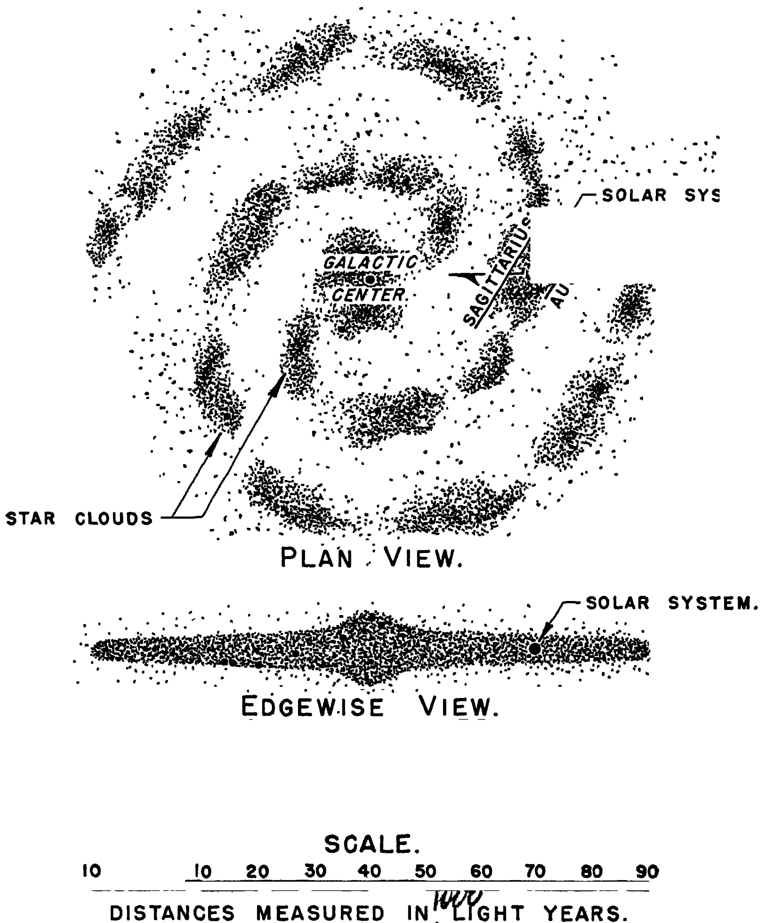


FIG. 192. Our Galaxy

eye are in this "local cloud." The size of this local cloud, or local system, is uncertain, but it has been estimated as 7,000 light years by 20,000 light years. The Sun is moving through this local cloud or swarm of stars, at a speed of twelve miles per second like an

individual bee in a swarm. This motion, approximately away from Sirius and toward Vega, was referred to on page 396.

Rotation of Our Galaxy. The rotation of our galaxy is measured with the spectroscope. Stars about as far away as the central clouds of our galaxy, some to the right and some to the left of the center should be used. Only very bright objects can be observed at that distance. Results have been derived from O-type and B-type stars, Cepheid variables, and planetary nebulae. The different methods agree almost surprisingly well. The entire galaxy is rotating about the central star clouds, and the rotation is carrying our local star cloud, including the Sun and solar system, in the general direction of the constellation Cepheus at a speed of 175 miles per second.

The results for our galaxy are summarized in the following table (see Fig. 192, page 430):

TABLE XVIII. FIGURES FOR GALAXY

1. Diameter	100,000 light years, or a little less
2. Thickness of galaxy	5000 light years at edge, 15,000 light years for central clouds
3. Distance of center	30,000 light years from us
4. Direction of the center	in star clouds in Sagittarius
5. Motion of local cloud	Velocity 175 miles per second in direction of Cepheus
6. Number of stars	100 billion

OTHER GALAXIES

For nearly one hundred years it has been known that many of the nebulae are spiral in form. These spiral "nebulae" are now known to be other galaxies. The typical exterior system shows two arms coiled about a central nucleus, the normal spirals. Second type shows two arms starting from the ends of a central bar, the *barred spirals.* Third type is the *edgewise spiral,* usually with a dark rift across the nucleus. Fourth type shows a circular or elliptical shape, with no trace of spiral structure. These are the *elliptical* spirals. Finally, there are some which show neither spiral structure nor elliptical shape. They are irregular in form and are termed *irregular.*

Distribution of Galaxies. Long before their nature was understood, it was known that the spiral "nebulae" were not found in the Milky Way. It is known now that this is because of the obscuring

effects of dark nebulous material which are clouds of gas and dust. The dust obscures stars and other objects behind the cloud. The

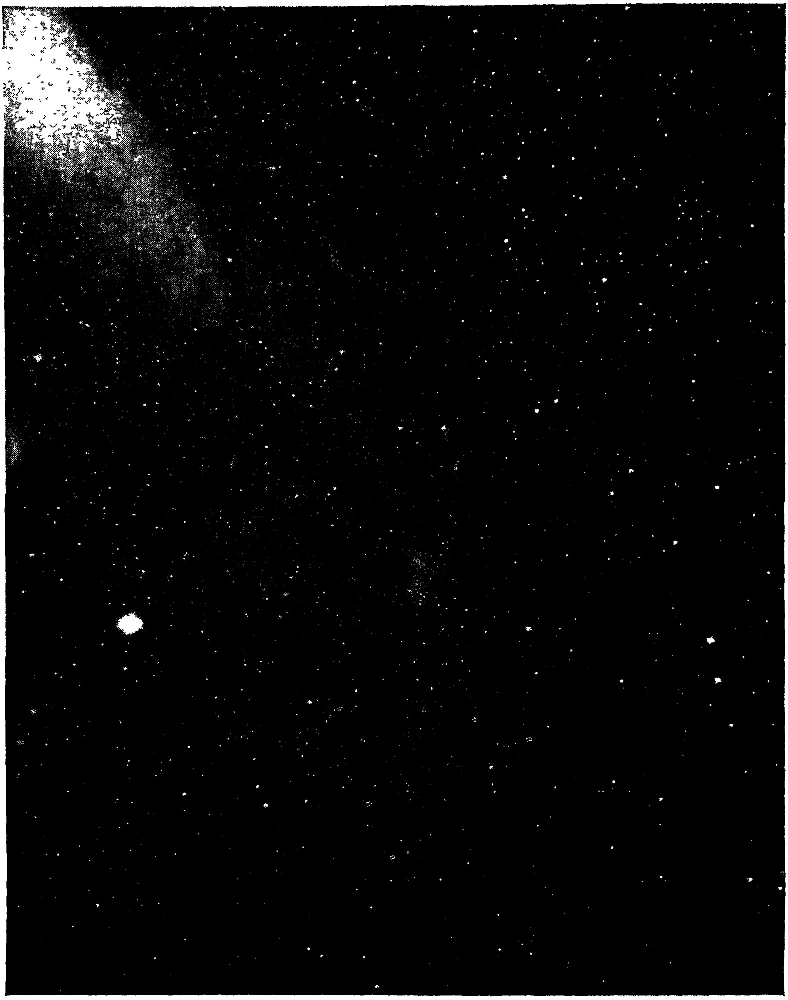


FIG. 193. A Portion of the Andromeda Galaxy, showing Resolution into Individual Stars. Photograph from the University of Chicago Press

galaxies cannot be seen in the Milky Way and in other regions covered by nebulous material.

Distance of Galaxies. The distance of galaxies can be determined, or at least estimated, in four different ways. The first obtains distances from the Cepheid variable stars. This is the most reliable method, and it was used by Dr. Hubble in determining the distance of the Andromeda galaxy (M31). He searched the plates especially for Cepheid variables and found more than thirty in the Andromeda spiral. It was necessary to obtain a considerable number of photographs to secure the light curves and periods of these variables. Then, using the period-luminosity law, he calculated the distance of the Andromeda "nebula," and found it to be 800,000 light years. This result was announced in 1924. Cepheid variables cannot be observed well enough with the 100-inch telescope for the use of this method for distances much more than 1,000,000 light years. With the 200-inch, however, it should be possible to apply this method to galaxies as far away as 3,000,000 light years.

The second method obtains distances from the assumption that novae of the ordinary type and the brightest stars in the exterior galaxy are of average brightness for those stars. From the nearer galaxies for which Cepheid variables are available, it appears that this method should give reasonably accurate distances as far as these stars can be observed, which is about 7,000,000 light years at present. Supernovae of average absolute magnitude −14 can be used to enormously greater distances.

The third obtains distances from the total brightness of the galaxy. On the assumption that a galaxy is about average in brightness, its distance can be estimated from the apparent brightness.

The fourth obtains distances from the red-shift or by the velocity-distance relation. This method will be explained in the paragraphs on Motion of Galaxies.

The Andromeda Galaxy. The spiral nebula in Andromeda, M31, is the closest of the spiral galaxies, and the only one discovered before the days of the telescope. Photographs with large telescopes of the central clouds of that galaxy resemble, almost surprisingly, photographs with small instruments of the central clouds of our own galaxy, those in the direction of Sagittarius. The Andromeda galaxy has been found to contain nearly all the features of our own galaxy. It contains numerous Cepheid variables similar to those in our galaxy, and over one hundred novae, or temporary stars, have

been found. It has bright and dark nebulous material and many globular clusters. The brightest stars have about the same luminosity as the brightest stars in our galaxy. From the Cepheid vari-

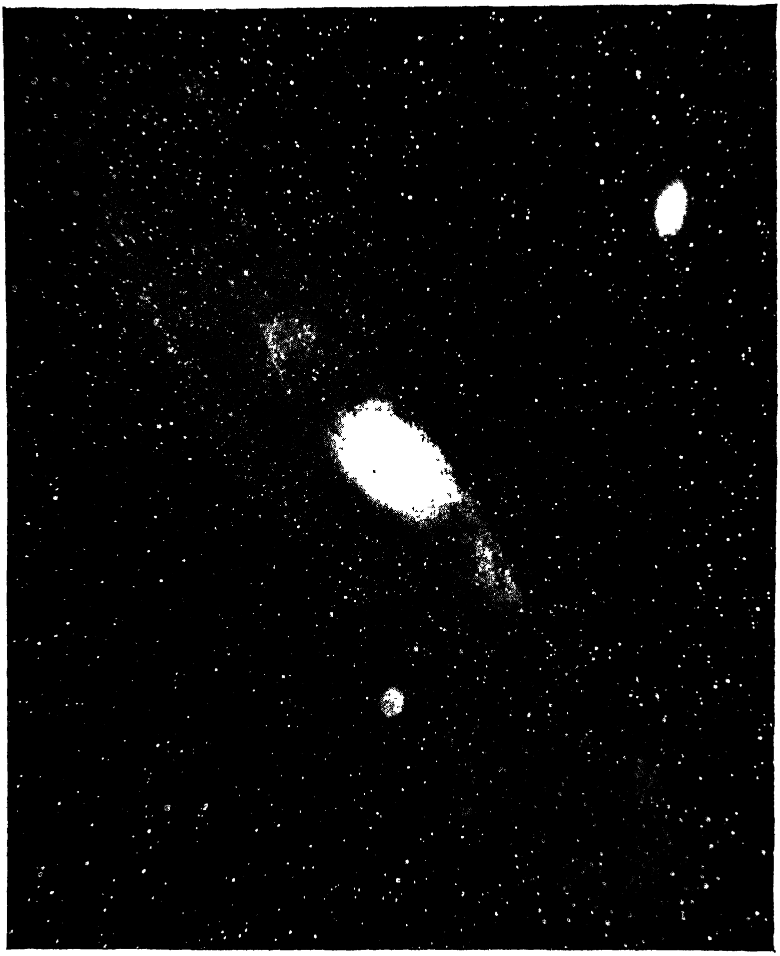


FIG. 194. The Galaxy M31 in Andromeda. Photograph from Yerkes Observatory and University of Chicago Press

ables the distance can be computed just as for star clusters within our own galaxy.

Figures for the Andromeda galaxy are:

Diameter	80,000 light years
Distance	800,000 light years
Rotation, central parts	period of 11,000,000 years
Rotation, outer parts	period of 92,000,000 years

The Andromeda galaxy is the most distant object visible to the naked eye. So one answer to the question, "How far can a person see?" would be, "With the naked eye 800,000 light years, and few objects seen with an ordinary telescope are more distant." Of course only the nucleus of the galaxy is visible to the naked eye, and on ordinary photographs it appears only about 40,000 light years in diameter, or half that obtained with the best equipment.

A few smaller galaxies are as near as M31 in Andromeda. The nearest are the irregular ones known as the clouds of Magellan. The large Magellanic Cloud is 11,000 light years in diameter and at a distance of 85,000 light years. The smaller Magellanic Cloud is 6,000 light years in diameter and 95,000 light years away.

Supernovae in Other Galaxies. A supernova appeared in the Andromeda galaxy in 1885, and several have appeared in other galaxies since. Most of them have been found with the equipment at Mount Wilson and Mount Palomar. At Mount Palomar, a Schmidt camera of 18-inches aperture and a focal ratio of about f/2 has been used for this work. Supernovae are distinguished from ordinary novae not only by their much greater absolute magnitude (giving about 5,000 times as much light as ordinary novae), but also by certain spectral lines easily detected by astronomers if the stars are near enough for spectroscopic observation.

Motions of Galaxies. One of the surprising facts of observation is that for practically all the galaxies (spiral nebulae) there is a shift of spectral lines toward the red. If this is interpreted as a true velocity shift, velocities up to 26,000 miles per second are indicated, and the velocity is proportional to the distance of the galaxy for those galaxies for which we have reasonable determination of the distance. Two interpretations have been suggested for this shift. The first is that it represents a real velocity, or motion. Interpreting this shift as due to a real velocity, or motion, one finds that the universe must be expanding. In a cloud of expanding steam each particle of vapor is separating from each other, and the far-

ther apart two particles are, the more rapidly they separate. Hence, if the galaxies are separating, and with a speed proportional to the distance, our universe of galaxies must be expanding.

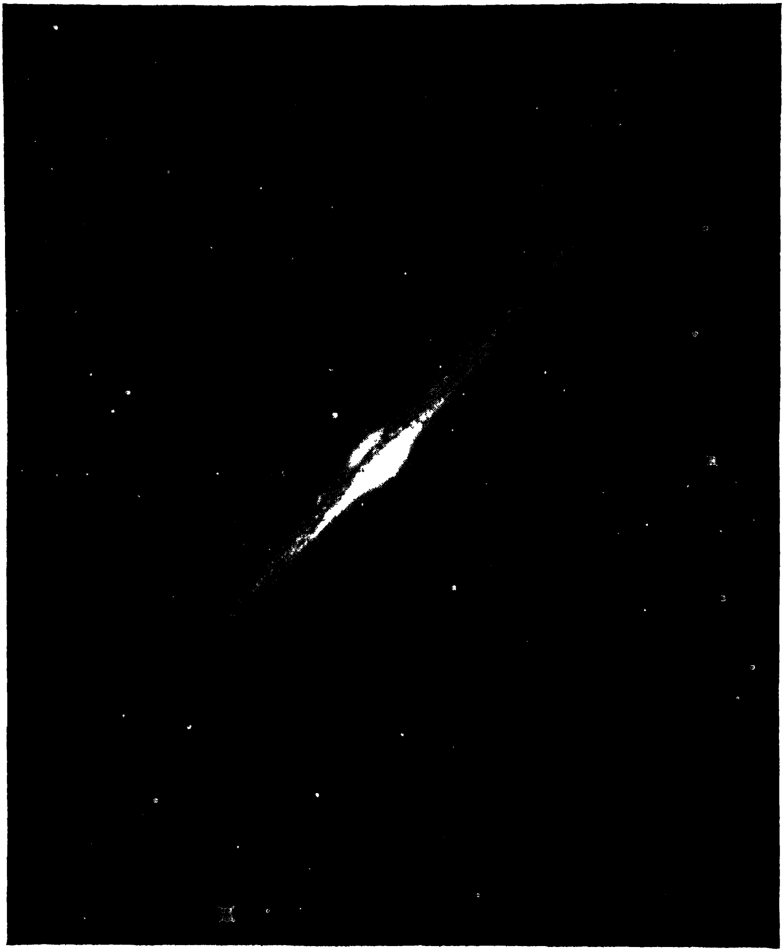


FIG. 195. The Edge-on Galaxy N.G.C. 4565 in Coma Berenices. Photograph from Yerkes Observatory and University of Chicago Press

The second interpretation is that, in the course of hundreds of thousands, or millions, of years, there is a loss of energy in the light. This loss of energy, inappreciable for objects in our own

galaxy, would produce a shift in the spectral lines toward the red for the more distant galaxies. If the loss of energy is proportional

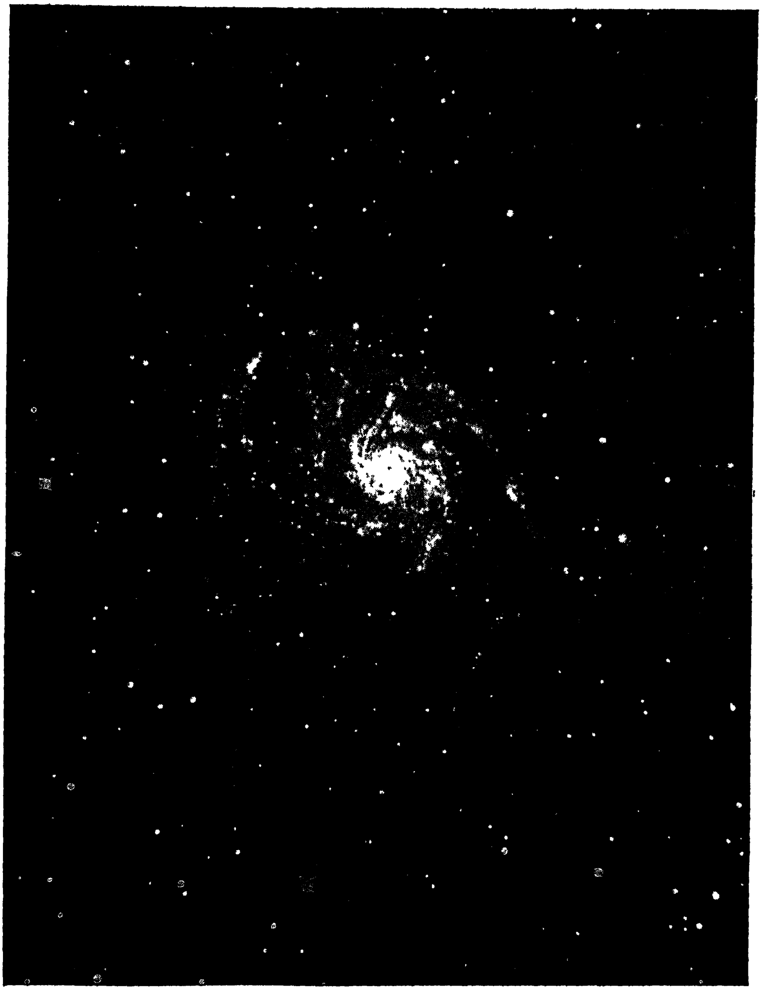


FIG. 196. The Galaxy M101 in Ursa Major. Photograph from the Yerkes Observatory and the University of Chicago Press

to the time since the emission of the light, the resulting shift would be proportional to the distance of the galaxy.

Astronomers are by no means certain as to what is the correct interpretation of this red shift, or apparent motion, of the galaxies. Probably the majority are inclined to interpret it as a réal motion, but even though it is not understood, it furnishes a very useful method of determining distances.

The Number and Space Distribution of Galaxies. A photograph made with the 100-inch telescope will reach stars of the 21st magnitude, or stars that are as much fainter than Alcor as the full Moon is brighter. On photographs taken with the 100-inch telescope, the other galaxies are just about as numerous as the faint stars in our own galaxy. It is estimated that the 100-inch telescope reaches out to a distance of 500,000,000 light years, and that there are 100,000,000 galaxies within that radius. The galaxies are just as numerous in those most distant regions as in the nearer regions.

Grouping of Galaxies. The stars in our own galaxy are grouped into double stars and clusters, and it is found that these galaxies, each containing billions of stars, are grouped in much the same way. About one galaxy in twenty-five is a double galaxy, the distance between the edges being less than the diameter of either component. The galaxies are grouped also into larger assemblages, or clusters, in which the number per unit of volume is several hundred times that for the intervening space. Dr. Shapley has used the term "super-galaxy" for these assemblages. The nearest super-galaxy is 7,000,000 light years from us, in Virgo.

Serious study of the exterior galaxies dates back only to about 1920. At that time it was not known definitely that the spiral "nebulae" were exterior systems. Since that time distances have been pushed out to an estimated figure of some 500,000,000 light years. The radius of the visible part of the universe will be increased greatly by the 200-inch telescope at Mount Palomar and by the powerful Schmidt telescopes which are planned.

Exercises

1. Define the term galaxy.
2. Name the classes of star clusters and give some examples of each class.

3. What are the ~~relative~~ distances from us of the three classes of star clusters?
4. How are star clusters and nebulae named?
5. What real differences have been established between the green and white nebulae of Herschel? When was it finally ascertained just what the white nebulae are?
6. Name the classes of galactic nebulae, giving the characteristics and an example.
7. What are the three classes of diffuse nebulae?
8. Why is the Crab nebula interesting?
9. What shape did Herschel find for our galaxy?
10. How are the dimensions of our galaxy computed?
11. What do we mean by the local cloud of stars of which the Sun is a member?
12. Give for our galaxy the diameter, ~~thickness~~, distance of Sun from ~~of~~ center, direction of center, and estimated number of stars.
13. What is the velocity of our local cloud about the center of our galaxy?
14. Into what classes are the exterior galaxies divided?
15. How are the distances of the exterior galaxies determined?
16. Why is M31 of such importance?
17. How is the red shift in the spectra of the exterior galaxies explained?
18. Compare the number of the exterior galaxies with the stars in our own system.
19. What is a supergalaxy?

Appendix

CONSTELLATION NAMES

Name and Combining Form	Pronunciation
Andromeda (Andromedae)	an-DROM-eh-duh (an-DROM-eh-dee)
Aquarius (Aquarii)	uh-KWARE-i-us *or* uh-KWAY-ri-us (uh-KWARE-i-eye *or* uh-KWAY-ri-eye)
Aquila (Aquilae)	ACK-wi-luh (ACK-wi-lee)
Ara (Arae)	AY-ruh (AY-ree)
Argo (Argus)	AHR-go (AHR-gus)
Aries (Arietis)	AY-ri-eez (uh-RYE-eh-tis)
Auriga (Aurigae)	aw-RYE-guh (aw-RYE-jee)
Boötes (Boötis)	bo-O-teez (bo-O-tis)
Cancer (Cancri)	KAN-sir (KANG-kry)
Canes Venatici (Canum Venaticorum)	KAY-neez veh-NAT-ih-sigh (KAY-num veh-nat-i-KOE-rum)
Canis Major (Canis Majoris)	KAY-nis MAY-jer (KAY-nis mah-JOE-ris)
Canis Minor (Canis Minoris)	KAY-nis MY-ner (KAY-nis mih-NO-ris)
Capricornus (Capricorni)	kap-rih-KOR-nus (kap-rih-KOR-nigh)
Carina [of Argo] (Carinae)	kuh-RYE-nuh (kuh-RYE-nee)
Cassiopeia (Cassiopeiae)	kas-i-oh-PEE-yuh (kas-i-oh-PEE-yee)
Centaurus (Centauri)	sen-TAW-rus (sen-TAW-rye)
Cepheus (Cephei)	SEE-fyews (SEE-fe-eye)
Cetus (Ceti)	SEE-tus (SEE-tie)
Columba (Columbae)	koh-LUM-buh (koh-LUM-bee)
Coma Berenices (Comae Berenices)	KOE-muh ber-eh-NIGH-seez (KOE-mee ber-eh-NIGH-seez)
Corona Borealis (Coronae Borealis)	koh-ROE-nuh boe-reh-AY-lis (koh-ROE-nee boe-reh-AY-lis)
Corvus (Corvi)	KOR-vus (KOR-vie)
Crater (Crateris)	KRAY-ter (krah-TEE-ris)
Crux (Crucis)	KRUKS (KROO-sis)
Cygnus (Cygni)	SIG-nus (SIG-nigh)
Delphinus (Delphini)	del-FIE-nus (del-FIE-nigh)
Draco (Draconis)	DRAY-koe (drah-KOE-nis)

Name and Combining Form	Pronunciation
Eridanus (Eridani)	eh-RID-uh-nus (eh-RID-uh-nigh)
Gemini (Geminorum)	JEM-ih-nigh (jem-i-NO-rum)
Grus (Gruis)	GRUSS (GROO-is)
Hercules (Herculis)	HUR-kyou-leez (HUR-kyou-lis)
Hydra (Hydrae)	HIGH-druh (HIGH-dree)
Leo (Leonis)	LEE-oh (leh-O-nis)
Lepus (Leporis)	LEE-pus (LEE-po-ris)
Libra (Librae)	LIE-bruh (LIE-bree)
Lupus (Lupi)	LEW-pus (LEW-pie)
Lyra (Lyrae)	LIE-ruh (LIE-ree)
Ophiuchus (Ophiuchi)	of-i-YEW-kus (of-i-YEW-kye)
Orion (Orionis)	oh-RYE-on (oh-rih-O-nis)
Pavo (Pavonis)	PAY-voe (pah-VOE-nis)
Pegasus (Pegasi)	PEG-uh-sus (PEG-uh-sigh)
Perseus (Persei)	PUR-syews (PUR-seh-eye)
Phoenix (Phoenicis)	FEE-niks (fee-NIGH-sis)
Pisces (Piscium)	PIS-eez (PISH-i-um *or* PIS-i-um)
Piscis Austrinus (Piscis Austrini)	PIS-is aws-TRY-nus (PIS-is aws-TRY-nigh)
Puppis [of Argo] (Puppis)	PUP-is (PUP-is)
Pyxis [of Argo] (Pyxidis)	PIK-sis (PIK-sih-dis)
Sagitta (Sagittae)	suh-JIT-uh (suh-JIT-ee)
Sagittarius (Sagittarii)	saj-i-TAY-ri-us (saj-i-TAY-ri-eye)
(1) Scorpius (Scorpii)	SKOR-pih-us (SKOR-pih-eye)
(2) Scorpio (Scorpionis)	SKOR-pih-oh (skor-pih-O-nis)
Serpens (Serpentis)	SUR-penz (ser-PEN-tis)
Taurus (Tauri)	TAW-rus (TAW-rye)
Triangulum (Trianguli)	try-ANG-gyou-lum (try-ANG-gyou-lie)
Triangulum Australe (Trianguli Australis)	try-ANG-gyou-lum aws-TRAY-leh (try-ANG-gyou-lie aws-TRAY-lis)
Ursa Major (Ursae Majoris)	UR-suh MAY-jer (UR-see mah-JOE-ris)
Ursa Minor (Ursae Minoris)	UR-suh MY-ner (UR-see mih-NO-ris)
Vela [of Argo] (Velorum)	VEE-luh (veh-LOE-rum)
Virgo (Virginis)	VUR-go (VUR-ji-nis)

STAR NAMES

Name	Pronunciation
Acamar	AH-kuh-mar
Achernar	AY-ker-nar
Acrux	AY-kruks
Adhara	ad-HAH-ruh
Alcyone	al-SIGH-oh-nee
Aldebaran	al-DEB-uh-run *or* ahl-deb-a-RAHN

Name	Pronunciation
Algenib	al-JE-nib *or* al-JEN-ib
Algol	AL-gol
Alioth	AL-i-oth
Al Na'ir	al NAH-ir
Alnilam	al-nih-LAHM
Alphard	al-FARD
Alphecca	al-FEK-uh
Alpheratz	al-FEE-rats
Al Suhail	al soo-HAH-il
Altair	al-TAIR *or* al-TAH-ir
Antares	an-TAY-reez
Arcturus	ark-TEW-rus
Epsilon Argus	EP-si-lon AR-gus
Bellatrix	be-LAY-triks
Betelgeuse	BET'l-jers *or* BET-el-gerz
Canopus	kuh-NO-pus
Capella	kuh-PEL-uh
Caph	KAFF
Castor	KAS-ter
Beta Crucis	BAY-tuh KROO-sis
Deneb	DEN-eb
Deneb Kaitos	DEN-eb KAY-tos *or* DEN-eb KYE-tos
Denebola	de-NEB-o-lah *or* de-NEB-oh-luh
Dschubba	JEW-buh *or* JUUB-buh
Dubhe	DOOB-heh *or* DUUB-heh
Enif	EN-if
Etamin	et-uh-MIN
Fomalhaut	FOE-mal-hawt *or* FOE-mal-o
Hamal	HAM-al
Beta Hydri	BAY-tuh HIGH-dry
Kaus Australis	KAWS aws-TRAY-lis
Kochab	KOE-kahb *or* ko-KAHB
Marfak	MAR-fak
Markab	MAR-cab
Merak	MEE-rack
Miaplacidus	my-uh-PLAS-ih-dus
Mizar	MY-zahr
Nunki	NUNG-keh
Peacock	PEE-kok
Alpha Phoenicis	AL-fuh fee-NIGH-sis
Polaris	poh-LAY-ris *or* poh-LAIR-is
Pollux	POL-uks
Procyon	PRO-sih-on
Rasalague *or* Rasalhague	ras-al-HAH-gwee *or* rahs-al-HAY-gew
Regulus	REG-you-lus

Name	Pronunciation
Rigel	RYE-jel *or* REE-jel
Rigil Kentaurus	RIJ-il ken-TAW-rus *or* RIJ-'l ken-TAW-rus
Ruchbah	RUK-bah
Sabik	SAH-bik
Shaula	SHAW-luh
Sirius	SIRR-ih-us
Spica	SPY-kuh
Vega	VEE-guh

Table of Constants

1 meter = 39.37 inches

1 knot = 1 nautical mile per hour

1 nautical mile = 1.1516 miles = 1′ arc on the Earth's surface at the Equator

1 statute mile = 5280 feet

1 astronomical unit = 92,897,000 miles

1 light year = 5.9×10^{12} miles

1 parsec = 19×10^{12} miles = 3.26 light years

Acceleration due to gravity = 32.174 feet per sec^2 or 980.665 cm per sec^2 at 45° latitude

Velocity of light = 186,320 miles per second

Atmospheric pressure (normal at sea level) = 14.696 pounds per square inch

1 synodic month = 29.53 days

1 sidereal month = 27.32 days

1 mean solar day = 24 hours = 1440 minutes = 8.64×10^4 seconds

1 sidereal day = 23 hours 56 minutes 4 seconds mean solar time

1 tropical year = 365.2422 mean solar days = 366.2422 sidereal days

1 sidereal year = 365.256 mean solar days

1 calendar year = 365.2425 days

Absolute zero = -273°.2 C = -459°.8 F

2 π radians = 360°

1 radian = 57° 17′ 44″.8 = 57°.2958

1° = 0.017453 radians

π = 3.141,592,653,589,793,238,462,643,383,279, or roughly, 3.1416

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